CHILLED PIPE EFFECTS

ON STREAMS

Rev. 2

ALASKA SEGMENT

ALASKA NATURAL GAS TRANSPORTATION SYSTEM

287-A

Alaskan Northwest Natural Gas
Transportation Company

CHILLED PIPE EFFECTS

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ALASKAN NORTHWEST NATURAL GAS TRANSPORTATION COMPANY

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PRELIMINARY

CHILLED PIPE EFFECTS ON STREAMS

PICK-UP

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REV. NO.	REMARKS	APPROVED: ORIGINATOR	APPROVED: ENGINEERING	APPROVED: ENVIRONMENTAL AFFAIRS	APPROVED: CONSTRUCTION
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NORTHWEST ALASKAN PIPELINE COMPANY	DOC. NO.	
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1.0 INTRODUCTION

The Northwest Alaskan Gas Pipeline will be installed in a buried mode throughout its alignment except at certain specific river crossings. Since the pipeline will be operated below 32°F, the presence of a chilled pipe in wetlands, streams and rivers crossed by the pipeline may tend to modify the thermal regime of the streambed materials and consequently alter the dynamic behavior of the stream systems. These consequences will be evaluated for every single crossing encountered along the alignment. If and where required, special design solutions or crossing alternatives will be undertaken to ensure that adverse effects on the stream environments and adjacent facilities do not occur.

The design intent stated in the foregoing notwithstanding, the Federal and the State agencies have expressed concerns regarding NWA's intent to cross in a buried mode the waterbodies located along the ANGTS alignment. These concerns were stated by the agencies in a letter addressed to NWA from the State Pipeline Coordinator's office as follows:

(1) Primary Physical Effects

(a) Alteration of natural flow regimes (for example, forcing subsurface flows to the surface with subsequent promotion of aufeis development and depletion of flows downstream); and

(b) Decreased water temperature.

(2) Secondary Physical and Biological Effects

(a) The inducement or acceleration of aufeis;

(b) Erosion resulting from aufeis-induced channel alterations;

(c) Stream channel changes;

(d) Alterations in natural springs and subsequent downstream changes;

(e) Alterations or elimination of open water leads resulting in reduction of dissolved oxygen concentrations below the acceptable minimum levels;

(f) Temporary blockage to fish movement resulting from aufeis (physical barrier) or decreases in water temperature (physiological barrier), including concerns for spring or fall migrating fish of all age classes;

(g) Alteration or elimination of overwintering habitat for fish and wildlife (for example, fish overwintering areas, changes in riparian habitats, or inundation of riparian zones by aufeis);

(h) Decreased survival of eggs of fall or winter spawning fish species; and

(i) Decreased survival of benthic invertebrates.

In response to the agencies' concerns, NWA put together a comprehensive program to address the issues. A two-fold approach was suggested which is described below.

The first approach called for the installation of a chilled pipe across a stream typical of the streams crossed by the pipeline along the alignment. Instrument the crossing, collect and analyze data to determine the effects of the chilled pipe on the stream's regime. Use this information in the design of stream crossings.

This approach was not pursued, however. The test would have been very restrictive and data based upon tests carried out at only one stream would be difficult to extrapolate to other types and sizes of streams. Additionally, the test would have been expensive and information would not have been available for final design. The agencies concurred with this decision and the idea of the test was abandoned.

The second approach called for using and/or developing analytical techniques to evaluate the effects on the thermal and hydrological regimes of streams due to the presence of a chilled pipe. This approach offered the flexibility of analyzing the chilled pipe effects on streams of all types and sizes. It was decided to pursue this direction of investigation with the concurrence of the agencies. The plan of action included:

biological approach also suggested

A. Use the EPR geothermal computer model to evaluate the effects of a chilled pipe buried in a location with standing water. This situation was conceived as the worst case scenario, since with no water flow heat exchange between the water and the chilled pipe would be expected to be the greatest.

Twelve hypothetical cases were proposed combining burial depth, types of soil and trench backfill, pipe without insulation and with 6 inches of insulation. Depths of cover proposed were 30 and 48 inches using silty soil with silty backfill, silty soil with granular backfill and granular soil with granular backfill. All cases were to be simulated over a 25-year period using a 15°F pipe temperature. However, this approach was modifed as described in Subsection 3.0.

B. Develop a mathematical convective heat transfer model incorporating the mechanism of phase change and mass flow to simulate conditions expected to be encountered at stream crossings.

This report addresses the agencies concerns regarding the possible detrimental effects of burying a chilled gas pipeline in the wetlands, streams and rivers of Alaska, and goes on to show that NWA is fully cognizant of these effects and that NWA has adequate and suitable design and design alternatives to ensure that the presence of a chilled pipe will not adversely affect the environments of Alaskan waterbodies.

The report discusses the results of the EPR thermal analyses, the mathematical convective heat transfer model, PORFLOW-F, and the result of sensitivity studies using the convective model. Also, *the report provides the applicable methodology that NWA proposes to follow in designing the wetlands, streams and river crossings.

Section 2.0 summarizes the conclusions resulting from these studies and the approach that NWA plans to follow in crossing the streams encountered along the pipeline alignment from the north slope to the Canadian border.

Section 3.0 details the work carried out under item 'A' mentioned above, i.e. determining the effects of a chilled pipe crossing a stream using the EPR thermal model. This was considered as the worst case situation and some interesting conclusions have resulted from this analysis.

Section 4.0 contains a discussion of the groundwater flow/heat transfer model, PORFLOW-F, as outlined under item 'B' above. Results of the sensitivity studies are also provided in the section.

Section 5.0 presents the design methodology to be used in analyzing potential chilled pipeline effects on individual stream crossings along the gas pipeline route. Design alternatives for controlling the potential effects of stream temperature depression and groundwater flow alteration are also presented.

← Section 6.0 mitigation "operational phase"

2.0 CONCLUSIONS

The primary objectives of this report are to present the results of analyses of the effects of a buried chilled gas pipeline on streams and related aquifers and to establish a design approach to be implemented during detail design to preclude or control potentially adverse effects of the pipeline on adjacent facilities and the environment.

The design approach presented provides for sequential assessment and analysis of stream crossing locations to identify an appropriate design solution for each crossing. The analysis procedures and design alternatives to be implemented during detail design are based in part on the results of the computer modeling. The major conclusion resulting from these analyses are presented below.

2.1 SUMMARY OF CONCLUSIONS FROM EPR ANALYSIS

The EPR thermal computer model, which is limited to conductive heat transfer, was employed to analyze generalized worst case conditions, i.e. shallow streams having no stream or groundwater flow, lowest gas temperatures, and gravelly soils.

The following general conclusions can be drawn from the results of these analyses:

- An uninsulated chilled pipe buried 8 feet or less below a sensitive waterbody could lower water temperatures and increase the duration of the frozen period.

- The use of pipe insulation (three inches or five inches) significantly reduces the effects of a chilled pipe on stream and streambed temperatures. Five inches of pipe insulation provides minimal additional improvement of surface effects compared to three inches of insulation. The climatic conditions dominate stream temperatures for the insulated pipe cases.

  climatics dominate if isolated

- The frost bulb growth in simulations for an uninsulated pipe under static stream is extensive (almost 21 feet in 5 years). The use of three or five inches of pipe insulation

  significantly further reduces the size of the frost bulb but the frost bulb continues to grow at a reduced rate throughout the ten-year simulation periods. Use of five-inch insulation further reduces the frost bulb growth.

  insulation only delays growth

this worst case is for no water movement !!! remember that in comments

- Simulations without surface water indicated deeper frost bulb growth compared to simulations with twelve inches of surface water, especially for the cases with deeper pipeline burial depth.

- Simulated breakup and freeze-up dates are significantly altered by the uninsulated pipe. The use of three or five inches of pipe insulation significantly reduces this effect. The maximum deviation from the control is six days using three-inch pipe insulation compared to 82 days for uninsulated pipe. Only slight differences are obtained comparing the effects of three- and five-inch insulation thicknesses on freeze and thaw dates.

- Alteration of freeze and thaw dates is less for the simulations using the permafrost environment as compared to those using the non-permafrost environment. Maximum deviation of stream temperatures in comparison to controls occurs during frozen periods for the permafrost simulations and during unfrozen periods for the non-permafrost simulations.

- Results of simulations for four- and eight-foot cover depths indicate deeper burial decreases effects on surface temperatures and decreases alterations of freeze and thaw dates. These effects, however, are not substantial. A more significant effect of deeper burial is to increase the effective frost bulb growth around the chilled pipe. These results emphasize the predominance of the surface heat balance on the thermal regime of the water body. An important implication of these results is that deeper burial may be used effectively to reduce potential blockage of groundwater only when deep burial places the pipe in a less permeable zone (i.e., either frozen zones or other zones having a lower hydraulic conductivity) thereby leaving a greater area above the pipe to convey groundwater.

2.2 SUMMARY OF CONCLUSIONS FROM PORFLOW-F ANALYSES

The PORFLOW-F coupled groundwater flow and heat transfer computer program was used to investigate potential groundwater interactions with the chilled pipeline. Results of the sensitivity analysis of output variables to various hydrogeologic input variables and of the investigative analyses simulating pipeline operation are summarized into the following major conclusions:

- Temperature variations for shallow waterbodies show higher sensitivities to a change in water depth than for deep waterbodies. Annual temperature variations are greater for shallow waterbodies than for deep waterbodies. Climate fluctuations control shallow soil temperatures and freeze-thaw cycles.

- Chilled pipeline operation is not expected to have a significant effect on groundwater recharge. Varying the groundwater recharge rates does not result in significantly thermal effects produced by a chilled pipeline as shown for the static groundwater simulations. However, infiltration of warm water in the summer may reduce the size of the pipeline frost bulb.

- Discharge of groundwater into a stream can maintain nearly constant subsurface temperatures. This discharge may retard the rate and extent of thermal effects of the pipeline.

- Diversion of groundwater flow to the surface and subsequent development of aufeis may occur in lateral groundwater flow areas due to the blockage of groundwater flow by the pipeline and attendant frost bulb. Groundwater flow to the surface may be terminated by an advancing freeze-front resulting in limited development of aufeis.

- Chilled pipeline operation in an area where hydraulic conductivty increases significantly with depth directly below the pipeline is expected to have very little impact on groundwater flow. Decreases in hydraulic conductivity with depth are as expected to have little effect on groundwater flow as long as the distance to the change exceeds three effective pipe diameters.

- Shallow subsurface temperatures show a strong correspondence to stream temperature variations. The chilled pipeline is not expected to significantly affect the temperatures of a flowing stream. Simulations employing warm summer stream temperatures (59°F) indicate a potential for the frost bulb growth to be reduced.

parallel?

shows little change if I read this correctly is this because 12 feet isn't a problem

3.0 ANALYSIS USING EPR THERMAL MODELING

The use of the EPR model, which is limited to conductive heat transfer, can be attributed to project needs for investigating potential chilled pipe effects prior to development of the coupled mass and heat transfer model. The approach outlined in the introduction was not followed explicity, however. Depths of cover were changed to four feet and eight feet to represent the range of probable burial depths in streams. Three and five inch insulation thicknesses were investigated rather than six inches because of design and construction considerations. Only gravelly streambed soils were modeled since this represented worst case, and finally, the simulations were held to five year durations rather than 25 years. Simulations or projections for the 25 year design life were postponed for analysis with the coupled mass and heat transfer model to remove some of the overconservatism of the investigation.

3.1 OBJECTIVES

The EPR thermal computer model is used to investigate thermal effects on stagnant waterbodies due to operation of a chilled gas pipeline. The simulated stream crossing represents a generalized worst case condition.

The effects of different insulation thicknesses, pipeline burial depths, surface water depths, and initial soil temperature conditions are investigated both in permafrost and non-permafrost environments. The results are used to assess the impact on stream temperatures, freeze-up and breakup dates, and frost bulb size.

3.2 METHODOLOGY

The EPR thermal model, the input data, and the simulation process are described in the following subsections. The matrix illustrating the specific variables used for each EPR run is shown in Figure 3-1. Five-year simulations were performed and the restart capability was utilized for three cases. The results of these simulations, although limited to conductive heat transfer, provide some useful information that can be coordinated with heat and mass transfer analyses to aid in identifying and assessing potential effects caused by chilled pipeline operation.

3.2.1 The EPR Model

EPR is a two-dimensional finite element thermal model which simulates heat conduction with a change of state for a variety of boundary conditions (Reference 1). The heat of fusion and changes in heat capacity and thermal conductivity due to thawing and freezing are taken into account in the program. It does not account for convective heat transfer due to surface or subsurface water flow. The model is used to simulate chilled pipeline operation in the subsurface. Frost advancement and temperatures above and below the chilled pipe are obtained from these simulations in order to examine thermal effects of the chilled pipeline operation.

An EPR grid has been developed for a 90-foot horizontal by 45-foot vertical cross section of ground with the pipe located at mid-length and perpendicular to the cross section. Figure 3-2 illustrates the typical grid used in the simulations of this study. Because of symmetry only half of the cross section is analyzed.

3.2.2 Input Data

3.2.2.1 Soil

The soil thermal and index properties used in the geothermal simulations are presented in Table 3-1. The soil specified for the analyses represents a saturated gravel which is characteristic of many of the streambeds in Alaska. The soil in the ditch zone is specified as a saturated granular backfill somewhat less dense than the native soil due to construction disturbance. Analysis using gravelly soils should produce conservative results.

3.2.2.2 Climate

The mean climatic data for Fairbanks Airport is used in the analyses and is presented in Table 3-2. Due to the significant influence of snow cover on ground temperature, the snow depth factor is adjusted to produce both non-permafrost and permafrost environments.

3.2.2.3 Insulation

The thermal properties for the circular insulation system used for selected configurations are shown in Table 3-1. Computer simulations for both the three-inch and five-inch insulation thicknesses are performed using equivalent thermal conductances of 0.371 and 0.231 Btu/hr-ft-°F, respectively for the combined pipe and insulation geometries based on an insulation conductivity of 0.015 Btu/hr-ft-°F.

3.2.3 EPR Thermal Simulation Process

The thermal analysis consists of a two step process. First, one-dimensional calibration runs are performed using full surface heat balance and adjusted snow depth factors until the desired equilibrium soil temperatures and freeze or thaw depths are generated.

Control runs are generated to represent the permafrost and non-permafrost environments with and without surface water. For non-permafrost environments the snow depth factor is adjusted until the one-dimensional runs produce equilibrium annual average soil temperatures of approximately 34°F (representative of typical unfrozen streambeds in Alaska) at about nine feet below the streambed. For permafrost environments, calibration of the snow depth factor using one-dimensional runs is continued until equilibrium annual average soil temperatures of approximately 31°F (representative of typical warm permafrost underlying streams south of Atigun Pass) at about nine feet below the streambed are achieved. Four separate one-dimensional calibrations are performed, i.e. one for each of the control runs as shown on Figure 3-1.

Second, using the same initial soil temperature profiles and adjusted snow depth factors as the control runs for the respective cases, two-dimensional simulations using the various water depths, pipeline burial depths and insulation thickness combinations shown in Figure 3-1 are performed for five-year durations. (The restart capability is employed for three configurations to provide ten years of simulation.) The environmental simulations commence in July and operation of the chilled gas pipeline is commenced five months later. The effect of the chilled gas is "phased in" by incremental temperature decreases starting two months prior to simulated start of operation.

3.3 RESULTS OF EPR THERMAL SIMULATIONS

Plots of isotherms for depth versus time for each of the simulations are shown in Figures 3-3 through 3-17. All simulations are for five years and only the 32°F isotherms are shown. Plots for the three restarts are not shown but results of these runs are summarized in Tables 3-3 through 3-7. The plots illustrate freeze and thaw advancement from the stream or ground surface in addition to extent of frost bulb growth above and below the pipe.

3.3.1 Freeze-Thaw Advancement from Surface

The control run (without pipe) for a non-permafrost environment with twelve inches of surface water shows a seasonal maximum frost penetration of approximately 3.8 feet from stream bottom (Figure 3-3). The corresponding simulation with a bare pipe (15°F) and a four foot cover depth indicates that the ground below the pipe is frozen to a depth of 20 ft. within the first year of operation. Seasonal thaw penetration into the streambed is less than one foot (Figure 3-4). Equilibrium of thaw depth with surface heat balance is quickly reached. Simulations with insulated pipe, including either three or five inches of insulation and with either four or eight foot cover depth, indicates minimal effect on the surface freeze/ thaw penetration depths

(Compare Figures 3-5, 3-6, 3-7, 3-8 to Figure 3-3). The appendages on the third and fourth year isotherms shown on Figures 3-7 and 3-8 represent remnant frozen areas resulting from the descending frost front. The dashed lines on all isotherms represent extrapolated results in contrast to interpolated results (between points representing monthly 32°F isotherm depths) shown by solid lines.

Results of simulations for a non-permafrost environment without surface water are presented in Figures 3-9 through 3-11. The control run (without pipe) shows a maximum seasonal frost penetration of approximately seven feet from the ground surface (Figure 3-9). Simulations with a pipe include four and eight feet of cover using three inches of insulation in each case. With four feet of cover, the seasonal thaw front penetrates to the insulation surface each year as shown in Figure 3-10. With eight foot cover the seasonal thaw depth continues to decrease throughout the simulation period to a depth of approximately five feet below ground surface (Figure 3-11). This condition constitutes a design consideration that must be resolved during design for use of 3 inch insulation.

Results of thermal simulations for a permafrost environment overlain by twelve inches of surface water are shown in Figures 3-12, 3-13, 3-14. Three inches of pipe insulation and cover depths of four and eight feet are simulated. Seasonal thaw penetration is approximately 4.5 feet below the streambed for the control run (Figure 3-12). The seasonal thaw penetration is reduced to approximately 3.5 feet below the streambed for both four and eight foot cover depths (Figures 3-13 and 3-14). For the shallow burial case, thawing is attenuated due to frost advancement from the chilled pipe.

Results of simulations for a permafrost environment without surface water are shown in Figures 3-15 through 3-17. The control run simulation indicates maximum seasonal thaw penetration of approximately eight feet (Figure 3-15). Three inches of pipe insulation and cover depths of four and eight feet are simulated. The seasonal thaw penetration extends to the insulation surface with four foot burial depth. Yearly frost bulb growth above the pipe extends less than one-half foot before joining the freezing front advancing down from the surface (Figure 3-16). With eight feet of cover, the seasonal thaw depth extends to approximately 6.5 feet below the surface (Figure 3-17). This is a reduction of approximately 1.5 feet compared to the control case.

3.3.2 Frost Bulb Growth

Results of the frost bulb growth around the pipe for the non-permafrost 5-year simulations are shown in Figures 3-3 through 3-11 and are summarized in Table 3-3. Table 3-3 also presents the results of the three 10-year simulations (employing the restart capability. The rapid frost bulb growth for the bare pipe case indicated that no additional bare pipe simulations were needed as this development is unacceptable. With twelve inches of surface water, the use of five inches of pipe insulation results in less than one-half foot of frost bulb growth below the bottom of pipe for both four and eight foot cover depths. The four foot cover depth produces slightly less frost depth 0.43 ft vs. 0.49 ft (Figures 3-6 and 3-8). Three inches of pipe insulation result in frost penetration depths of 2.35 ft. and 2.49 ft. for four and eight foot burial depths, respectively. (Figures 3-5 and 3-7).

Extended simulations for the cases employing three-inch insulation indicates frost bulb depths of 3.60 ft. at the end of the tenth year for four foot cover and 4.11 ft. at the end of the ninth year for eight foot cover. The frost bulbs in each case continue to grow.

The effect of surface water presence on frost bulb growth is evident where 8 foot cover depth was used. Frost penetration was 2.49 ft. with 12 inches of surface water and 3.99 ft. without surface water. For the simulations using 3 inches of insulation and four foot cover, the presence of surface water showed no effect as shown on Table 3-3 and on corresponding figures.

The effect of deeper burial on frost bulb growth is not substantial for the simulations with 12 inches of surface water and either 3 or 5 inches of insulation as evidenced from Table 3-3. However, without surface water and with 3 inches of pipe insulation the 5 year frost bulb growth is significantly larger with deep burial. Frost penetration is 3.99 ft. for the 8 foot cover vs. 2.14 ft. for 4 foot cover.

3.3.3 Freeze and Thaw Dates

Results of the simulations of chilled pipeline effects on stream bottom freeze and thaw dates are presented in Table 3-4. Dates are derived from straight line interpolation between data points of 32°F isotherm depth vs. time plots of EPR output for the fifth year of each simulation. Results of simulations including both permafrost and non-permafrost environments are included in the table.

In the simulations, the presence of an uninsulated pipe accelerates the freeze date (82 days) and delays the thaw date (23 days) of the stream bottom in comparison to the control. With pipe insulation, the stream freeze date is accelerated by a maximum of 6 days maximum and the stream thaw date is delayed by 2 days. An increase in insulation thickness from three to five inches and increase in burial depth provide slight improvement in reducing these effects.

3.3.4 Stream Temperature Depression

The effects of the chilled pipe on monthly stream temperatures are presented in Table 3-5. The results represent simulated stream temperatures at the stream bottom directly above the pipe centerline for the fifth year of operation. Temperature differences between simulations, including pipeline operation, and the appropriate control are also presented in parentheses for ease of comparison.

The stream bottom temperature is reduced nearly 21°F in simulations with an uninsulated pipe as shown for month 43. Use of five inches of pipe insulation results in a maximum stream temperature depression of 2.8°F in the non-permafrost simulation. This reduction occurs during month 51 when the stream is unfrozen.

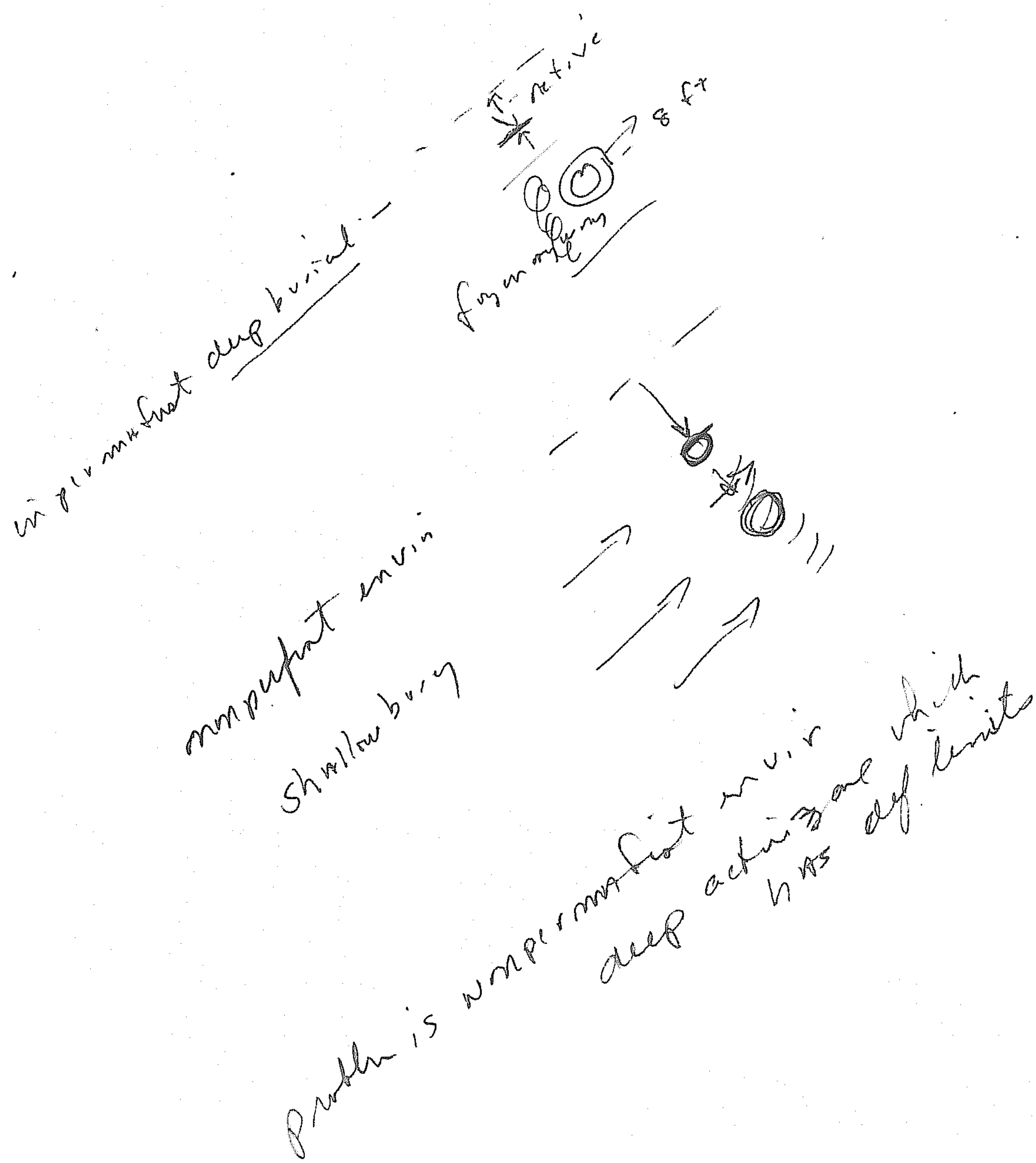
With three inches of insulation, the maximum stream temperature depressions are 5.7°F for the permafrost environment and 3.7°F for the non-permafrost environment. The 5.7°F reduction occurs when the stream is frozen (month 45 when the control indicates the lowest temperature) and the 3.7°F reduction occurs when the stream is unfrozen (month 51).

Deeper burial provides a slight improvement in reducing the effects stream temperature as indicated for both environments and insulation thicknesses.

Table 3-6 shows temperature values at 11 and 19 ft. from pipe centerline for run JV0120 which simulates three-inch insulation and four-foot burial in non-permafrost environment. This is the run which shows the maximum stream temperature depression during a period of unfrozen conditions. These results indicate how the chilled pipe effects on stream temperature depression is reduced with distance from the chilled pipe. At eleven feet from centerline, the maximum reduction in temperature is 1.8°F. At 19 feet, the maximum reduction is 1.0°F compared to 3.7°F reduction directly above the pipe. It is expected that stream flow mixing would likely reduce the maximum water temperature depression to well below 3.7°F.

Generally the most critical periods for stream temperature alterations are considered to be just after spring breakup and just before freeze-up. The results of the simulations presented in Table 3-5 indicate temperature deviations of generally less than 1.5°F during these periods. Even more important, surface water mixing is expected to reduce this effect.

Results of streambed temperature depression for simulations without surface water are presented in Table 7. Results of three-inch pipe insulation and burial depths of four and eight feet are compared to controls for permafrost and non-permafrost environments. The maximum temperature depression at ground surface of 4.8°F occurs with the shallow burial in the permafrost environment. The maximum temperature deviation in the non-permafrost environment is 3.4°F, which occurs in simulations using four foot cover depth. These maximum deviations occur during frozen periods. During unfrozen periods the deviations are generally less than one-half degree within both environments. Deeper burial significantly lessens the stream temperature depression caused by the chilled pipe presence.



4.0 PORFLOW-F SENSITIVITY ANALYSIS

The PORFLOW-F computer model has been developed for simulating both stream flow and groundwater flow, which are coupled to the heat transfer equations in order to simulate convective heat transfer. A preliminary study has been performed to show that PORFLOW-F and EPR give comparable results for heat conduction simulations utilizing analytical solutions for several heat conduction cases (Reference 2).

4.1 MODEL DESCRIPTION

PORFLOW-F is a mathematical model which simulates groundwater flow and heat transfer through porous media; see references 3 and 4 for the mathematical development and numerical techniques employed in the model. The model has the ability to simulate the reversible change in phase from water to ice within the porous media. It incorporates two mechanisms of heat transfer, namely convection and conduction. Interaction between the porous media and contiguous boundaries, such as an overlying stream and an underlying impermeable boundary are standard features. The model also considers heat transfer between the atmosphere and 1) a stream or, 2) directly with the porous media. The model uses finite-difference techniques to approximate the coupled two-dimensional equations governing groundwater flow and heat transfer. The numerical algorithm developed to model phase change is implicitly coupled to the solution of the groundwater flow and heat transfer equations.

PORFLOW-F tabular printout may be obtained at various times throughout a simulation for the following output arrays:

- X-directional component of groundwater flow velocities between grid cells.
- Y-directional component of groundwater flow velocities between grid cells.
- Total hydraulic head values at each grid point.
- Temperature values at each grid point.
- Ice content values for each grid cell.
- Values for the five variables listed above at a selected reference point, at each time step.

An auxiliary contouring program is available for producing selected contour plots of temperature, hydraulic head and ice content. Groundwater flow vector plots can be generated with this package also. These plots provide the most useful means of displaying the simulation results and they are used for comparing and analyzing the results of various simulations.

The model is capable of simulating transient flow within the porous medium, so that time-varying responses can be determined for seasonal variations in atmospheric and stream conditions.

4.2 SENSITIVITY ANALYSIS

An assessment of the sensitivity of various model output responses to variations in model input has been made, for details see reference 5, "PORFLOW-F Sensitivity Analysis".

- Input parameters examined include:
  - stream water depth
  - stream temperature
  - direction of groundwater flow
  - hydraulic conductivity of porous media
  - thickness of pipe insulation
- The output parameters examined include:
  - groundwater velocities
  - hydraulic head
  - subsurface temperature
  - ice content

The results of the sensitivity analyses include investigations of the effects of hydrogeolic variables in addition to investigations of the effects of pipeline operations.

The above parameters were chosen for examination within the sensitivity analyses because they are expected to be the most significant with respect to convective heat transfer effects and groundwater flow alteration. Sensitivities to variations in atmospheric heat exchange coefficients and effective air temperatures are not considered in this study.

Two grid schemes have been employed for the PORFLOW-F simulations, the difference between the two schemes being associated with the thickness of the insulation around the pipe. The dimensions of the modeled region are 200 feet long and 45 feet in depth. Figure 4-1 shows the regional cross sectional grid scheme, and Figure 4-2 shows a typical detailed grid section around the area of the pipe . Figure 4-3 shows five typical zones used in various simulations. Zone V represents a single point at the center of the pipe, while zone IV represents the combined effects of the pipe and the insulation having an effective thermal conductance which represents the combined properties of the pipe and insulation.

Values for soil thermal properties are presented in Table 4-1. These values are assumed to be constant for all simulations. Other values of soil thermal properties will be considered for use during detailed design. The surface boundary condition is modeled using an atmospheric simulation algorithm which uses available climatic data to determine surface heat exchange coefficients and effective air temperatures. Climatic data used for all simulations are shown in Table 4-2 for a complete year. These data are representative of mean values for the Fairbanks climate.

Other invariant input parameters used in the simulations pertain to the equation associated with the phase change mechanism. This equation is defined in Reference 1 and the coefficients used are representative of a coarse grain soil.

4.3 RESULTS

Undisturbed conditions are obtained for a simulation time of 5 years, for a given set of input conditions. This time period is usually sufficient to produce cyclical temperature patterns in the subsurface and allows time for initial transients to be dampened from the simulations. For the simulations involving pipeline operation, after undisturbed conditions are established the pipeline is included and operation is started six months from the beginning of the simulation (Note: The dormant period is not a part of this study). Simulations are conducted for 4.5 years after pipeline start-up. The fifth year simulation results serve as the basis for the following discussions.

4.3.1 Variations in Surface Water Depth

Five simulations were performed to analyze the sensitivity of subsurface temperature and ice content to variations in stream water depth. These simulations were performed using static groundwater conditions, and a range of stream water depths from 0 to 5.25 feet. These depths cover the range of expected natural variability for most static water bodies expected to occur with the pipeline alignment. Results from these simulations are shown in Figures 4-4 to 4-8. Figures 4-4 to 4-6 represent the variation of temperature with stream water depth at three locations below the surface water body: 0.5 feet, 2.4 feet and 9.8 feet.

These depths are examined to indicate the sensitivity of groundwater temperature to stream depth in the vicinity of the pipeline. Variations are considered for each month of the year.

Figure 4-7 shows annual temperature variations with stream water depth variation for those locations defined above.

Figures 4-4 to 4-6 indicate that subsurface temperature variations and temperature sensitivity to variations in stream water depth are dampened with depth. Figure 4-7 further illustrates these results. An increase in stream water depth dampens the groundwater temperature variations significantly. The annual temperature variations below a waterbody of 0.5 feet depth is 27°F, while below a 5.25 foot deep waterbody, it is only 4.8°F.

Figure 4-8 shows the variation in maximum freeze depth with stream depth variation. Results shown in this Figure indicate the same effects of stream water depth variation on frost penetration as shown for temperature responses. Frost penetration is substantially reduced below deep water bodies because of the dampening of the surface thermal effects due to the high thermal capacity of water.

In addition to the five simulations performed with variable stream water depth, four more simulations were conducted to examine the effect of the chilled pipeline on groundwater temperature and ice content. These simulations considered stream water depths of 1 foot and 5.25 feet for the case of an uninsulated pipe, with a gas temperature of 15°F (see Figures 4-9 and 4-10); and a 1 foot stream water depth, with pipe insulation being 3 inches and 5 inches (Figures 4-11 and 4-12). These last four simulations, although not directly associated with the sensitivity analysis process, have been used in conjunction with the results from the initial simulations to qualitatively examine the effects of stream water depth on groundwater temperature, with and without the pipeline.

Simulation results show that bare chilled pipe operation will substantially alter the ground thermal regime. Beneath both water bodies examined, the 32°F isotherm occurs around the pipe and extends to approximately 22 feet below the base of the pipe by the middle of the fifth year. This compares favorably with the results of the EPR analysis (approximately 21 feet as shown on Figure 3-4). For a stream water depth of 1 foot, thawing occurs at the surface and enough surface energy is transferred to reduce the frost bulb around the top of the pipe. For the deeper water body, thawing does not occur around the pipe because all of the surface energy is absorbed by the stream water body.

Application of circular insulation significantly reduces the effects of the chilled pipeline as shown in Figures 4-11 and 4-12. These simulation results are obtained using a 1 foot deep stream water depth. The frost bulb around the pipe waxes and wanes with climate fluctuations for both 3 inches and 5 inches of circular insulation (See Reference 5). In both cases the frost bulb is effectively thawed by the beginning of winter.

4.3.2 Stream Temperature Variations

Due to the high thermal capacity of a flowing stream, the temperature of the modeled flowing stream will not change due to climatic or groundwater conditions over the reach length being simulated. However, a stream is expected to affect the subsurface thermal regime over which it is flowing. In order to investigate these effects, a generalized "cold" and "warm" stream were selected from available data to conduct four simulations. Figure 4-13 shows the annual temperature profile for the two streams. In these simulations, static groundwater conditions were assumed and a 1-foot deep stream, flowing at 1 ft/sec was employed in each case. Simulated stream flow is assumed to cease when the stream temperature reaches 32°F.

Results obtained for the simulation of undisturbed conditions are shown in Figure 4-14 for the cold stream and 4-15 for the warm stream. In both cases, shallow groundwater temperatures closely correspond to the stream temperature. These figures demonstrate a strong sensitivity of subsurface temperature to stream temperature variations.

Figure 4-16 demonstrates the importance of stream temperature variation on the subsurface thermal regime. Frost penetration for the cold stream is substantially deeper (up to 3 times deeper) than below the warm stream.

Simulation results, including chilled pipeline operation with a gas temperature of 15°F and 3 inches of insulation, are shown in Figures 4-17 and 4-18 for the cold stream and the warm stream, respectively. Figure 4-17 shows the frost bulb around the pipeline extending slightly deeper than the frozen soil layer which develops under undisturbed conditions. The 32°F isotherm extends 3 feet deeper below the pipe than it does in the area unaffected by pipeline operation.

The maximum growth of the frost bulb around the pipe beneath the warm stream is shown in Figure 4-18. This frost bulb waxes and wanes with the temperature fluctuation of the stream (See Reference 5). In the summer, the frost bulb is totally thawed by November due to the thermal energy transferred by the stream at the surface. The frost bulb starts growing around the pipe once the stream temperature is reduced below 32°F and stream flow ceases. These results indicate that frost bulb growth can be significantly reduced by the presence of warm stream flow at the surface.

4.3.3 Groundwater Flow Direction

Three types of groundwater flow are examined: recharge, discharge, and lateral flow. Groundwater flow in recharge areas is dominated by flow that moves vertically down from the surface. In discharge areas, groundwater flow is directed toward the surface. Lateral flow is described by groundwater movement parallel to the surface. Lateral flow may occur in combination with either recharge or discharge flow but in these sensitivity analyses each component flow is analyzed separately.

4.3.3.1 Groundwater Recharge

Groundwater recharge rates may vary over a large range of values depending upon the hydraulic conductivity of the stream bed material. For this analysis, two averaged recharge rates are selected to examine the effects of recharge rates on subsurface temperature and ice formation around a chilled pipeline: 0.1 ft^3/ft^2-d and 1.0 ft^3/ft^2-d. The surface temperature is assumed to be maintained at 33°F throughout the simulation, which may be considered to be representative of a glacial fed stream.

For the cases simulated, the subsurface temperatures take on the temperature of the recharging groundwater. Therefore, the groundwater temperature remains at 33°F and there is no frost penetration in simulations for undisturbed conditions. The effects of introducing an uninsulated chilled pipeline, operating at 15°F, are shown in Figure 4-19. These results represent the conditions for the flow rate of 1.0 ft^3/ft^2-d. The results show a freeze bulb developing around the chilled pipe similar in size to the simulations of static groundwater and stream flow conditions (see Figure 4-9). The results for the lower recharge rate are very similar. The results show that temperature alterations and freeze bulb development are not significantly affected by variations in groundwater recharge rate for the cases selected here employing 33°F groundwater.

The effect of the chilled pipeline on groundwater flow is negligible in the simulations of recharge conditions. The primary effect is to reduce the area available for recharge in the modeled section due to frost bulb growth. As shown in Figure 4-19, recharge continues to occur either side of the pipeline as would be expected. The area affected by the pipeline and attendant frost bulb amounts to less than 10 percent of the modeled area in the simulations conducted in this analysis. This percentage would be much less were calculations to be based on the actual available area of recharge in the physical environment.

not true in permafrost

4.3.3.2 Groundwater Discharge

The sensitivity of temperature and frost penetration to variations in groundwater discharge was examined using a range of groundwater discharge rates from 0.01 ft^3/ft^2-d to 5.0 ft^3/ft^2-d. Discharge rates as high as 5 ft^3/ft^2-d occur at certain locations along the alignment, although generally only for short period. Incoming groundwater temperatures were varied from 33°F to 40°F. These ranges of values are expected to cover the range of possibilities along the pipeline alignment except in unusual occurrences.

Results of the various simulations are shown in Figures 4-20 to 4-22. These results indicate the sensitivity of groundwater temperature to discharge rates above 0.5 ft^3/ft^2-d. Below this value, discharge to the surface ceases to occur because of frost penetration from the surface. As shown in Figures 4-20 to 4-22 temperatures below a depth of 2 feet are maintained at the incoming groundwater temperature throughout the year, indicating no sensitivity to changes in flow for the rates above 0.5 ft^3/ft^2-d.

Results for simulations including uninsulated pipeline operation are shown in Figure 4-23. The groundwater discharge rate is 0.5 ft^3/ft^2-d in this simulation and the incoming groundwater temperature is 33°F. This simulation indicates that bare chilled pipeline operation is relatively unaffected by the occurrence of the groundwater discharge for the groundwater flow rate and temperature analyzed. The freeze bulb grows to a similar extent shown for static groundwater and surface water conditions (see Figure 4-9).

Effects of chilled pipeline operation on groundwater discharge, in these simulations, are not significant. As shown in Figure 4-23 (groundwater flow vector plot), groundwater is diverted around the pipeline and exits at the surface. The total flow is somewhat reduced due to the reduction in the cross-sectional area by the chilled pipeline and attendant frost bulb. However, this reduction is expected to be insignificant for most groundwater discharge areas when compared to the total area, where groundwater is discharging.

4.3.3.3 Lateral Groundwater Flow

Lateral groundwater flow is the predominant groundwater flow direction in alluvial stream environments underlain by thin aquifers. A large range of flow rates are expected to occur in these thin alluvial aquifers. High stream gradients and coarse grain soils in mountain streams and low gradients in lowlands streams are expected to define a broad range of lateral groundwater flow values.

The effects of variations in lateral groundwater flow on temperature and frost penetration was examined by considering four groundwater flow rate: 0.0, 0.1, 1.0 and 5.0 ft^3/ft^2-d. These flows are expected to cover the range of variability for most lateral flow conditions. The last value, although being rather large, was used to better examine the sensitivity of groundwater temperature to potentially high flows. A temperature of 33°F was assumed for the incoming groundwater. A static, one foot deep stream water body was included on the surface of the model area. Simulations for chilled pipe operation were conducted using these various lateral flow cases. Selected pipe configurations included a bare pipe, and a pipe covered with 3 inches and 5 inches of circular insulation.

Results indicating temperature sensitivity to lateral groundwater flow are shown in Figures 4-24 to 4-26. A significant effect of lateral groundwater flow is to increase the thermal capacitance of the soil. Temperature variations are reduced with depth as a result of this effect. Groundwater temperatures appear to be most sensitive to changes in lateral flow values at lower groundwater flow rates. As flow rates increase, groundwater temperatures tend toward the temperature of the inflowing water. This is particularly noticeable with increasing depth below the stream (See Figure 4-26).

Chilled pipeline operation, with and without insulation is incorporated into lateral groundwater flow simulations and typical results are shown in Figures 4-27 to 4-29. These figures indicate that the thermal capacitance of the lateral groundwater flow in these simulations is not sufficient to reduce the freeze bulb growth around a bare pipeline when flow rates are 1.0 ft^3/ft^2-d and incoming groundwater temperatures are 33°F. The dimensions of the freeze bulb are nearly the same as the freeze bulb simulated using static groundwater and stream flow conditions (see Figure 4-9). Application of three inches of circular insulation is effective in reducing the freeze bulb growth around the pipe. The freeze bulb is comparable in size, whether the lateral flow rate is 0.1 ft^3/ft^2-d or 1.0 ft^3/ft^2-d, indicating little sensitivity to variations in these flows at the lower groundwater temperature.

Figure 4-30 indicates how the thermal capacity of the lateral flow is significantly increased when the incoming groundwater temperature is increased to 40°F. As shown in this figure, the incoming groundwater supplies sufficient heat to prevent the frost bulb from growing around a chilled pipeline having 3 inches of circular insulation.

Any groundwater flow may alter the subsurface thermal regime, particularly if the flows are above 0.1 ft^3/ft^2-d (See Figure 4-25). For the analysis of low incoming groundwater temperatures, summer warming effects are reduced by the presence of cool groundwater flow. This effect is expected to be considerably altered beneath larger streams where the surface and groundwater temperatures exceed 33°F, as shown by the results employing 40°F groundwater.

Figures 4-27 to 4-29 show that operation of a pipeline in a lateral groundwater flow area does alter groundwater flow. In the simulations using an uninsulated pipeline, groundwater flow is redirected to the surface and beneath the pipeline. However, frost penetration from the surface reduces the upward flow and eventually stops all flow to the surface. This results in all groundwater flow being redirected beneath the chilled pipeline and attendant frost bulb (see vector plot in Figure 4-27). Application of 3 inches of circular insulation significantly reduces the growth of the frost bulb and thus the area of flow blocked by the pipeline.

4.3.4 Hydraulic Conductivity Variations

In order to investigate effects on temperature, ice formation and groundwater flow, simulations were performed using spatial variations of hydraulic conductivity. These variations were investigated using models representing:

- an increase in hydraulic conductivity with depth,
- a decrease in hydraulic conductivity with depth, and
- a decrease in hydraulic conductivity in the downstream direction.

Chilled pipeline operation was simulated under the second case to examine the effects of the pipeline in a thin shallow aquifer.

Results for the simulation representing an aquifer where hydraulic conductivity increases with depth are shown in Figure 4-31. In this case, groundwater flow is assumed to be lateral and the incoming groundwater temperature at the upstream boundary is 33°F. There are two units occurring below a static surface water body: the flow rate in the upper unit is 0.1 ft^3/ft^2-d (representing a hydraulic conductivity of 2 ft/d) and the flow rate in the lower unit is 5.0 ft^3/ft^2-d (representing a hydraulic conductivity of 100 ft/d). The upper unit is 10.5 feet thick. The results obtained for this simulation are very similar to the results obtained for the the undisturbed simulations using a homogeneous soil distribution and lateral groundwater flow of 0.1 ft^3/ft^2-d. This result may have been anticipated as the primary thermal variations occur in the upper few feet of the aquifer.

The second case represents a shallow aquifer of 17.5 feet thick underlain by an impermeable medium. A lateral groundwater flow of 1.0 ft^3/ft^2-d is assumed and its incoming temperature at the upstream boundary of the model is assumed to be 33°F. The results of the simulation shown in Figure 4-32 are very similar to the results obtained in the simulation for the same lateral groundwater flow through a homogeneous aquifer (Figure 4-28).

Chilled pipeline operation using 3 inches of circular insulation was incorporated into this model. Typical simulation results are shown in Figure 4-33. In comparison with Figure 4-28, it is clear that the results are nearly identical to the results obtained for the homogeneous aquifer having the same lateral groundwater flow. (Note that the 32.5 and 33°F contours were not plotted in Figure 4-28). These results indicate that a decrease in aquifer thickness for these flow conditions and groundwater temperatures does not significantly alter the thermal effects of the chilled pipeline.

The last investigation of hydraulic conductivity variations considers a decrease in hydraulic conductivity downstream. The model constructed for the simulation consists of a highly permeable aquifer adjacent to an aquifer having a much lower hydraulic conductivity. The hydraulic conductivity for the upstream aquifer is 50 times higher than for the downstream aquifer.

The results shown in Figure 4-34 show that the ground temperatures near the contact of the upstream and downstream units is significantly different from the homogeneous case. Groundwater discharging at the surface near the contact provides a mechanism for heat to be convected to the surface.

Generally, temperatures are maintained near the incoming groundwater temperature. In the winter months this convective heat transfer toward the surface slows frost penetration from the surface and may result in aufeis development. These results indicate that variations in horizontal stratigraphy may produce thermal and groundwater flow patterns at the contacts which vary dramatically from those obtained for homogeneous aquifer conditions.

4.4 SENSITIVITY ANALYSIS CONCLUSIONS

The sensitivity analysis results presented in this section indicate that thermal investigations conducted for stream environments should account for convective heat transfer mechanisms such as stream flow and groundwater flow. The most important hydrogeologic parameters identified in the analysis are:

- o Direction and rate of groundwater flow
- o Incoming groundwater temperature
- o Stream flow and associated stream temperature
- o Horizontal variations in hydraulic conductivity

Each of these factors has a strong influence on the thermal results of the PORFLOW-F simulations. Therefore, careful consideration should be given both in selection of input values for a simulation and in interpretation of the results from a simulation.

Results obtained for simulated undisturbed conditions and chilled pipeline operation are summarized in Table 4-3.

.1 ft³/ft²-d

50 x 20 aquifer

1000 ~~sq ft~~ x .1 ft³/~~ft²~~-d

100 ft³/day

180 ~~days~~ 100 ft³/~~day~~

18,000 ft³ water/season

20 feet wide X 150 X 6 feet deep

5.0 DESIGN PROCEDURES

This section contains the methodology which 1) presents the procedures for assessing chilled pipeline effects on stream crossings and potential impacts on the environment and adjacent facilities, 2) provides a means for selecting stream crossing designs that will limit development of adverse chilled pipeline effects, and 3) identifies alternative design concepts which are available for controlling all potentially adverse chilled pipeline effects that may be identified along the gas pipeline alignment. These procedures for chilled pipe effects are to be employed during detail design and will require compatibility with other design procedures (for frost heave and thaw settlement) to meet all design criteria specified in the Pipeline Design Criteria Manual.

Procedures for assessing chilled pipeline effects consist of two primary concerns, i.e. stream temperature depression and alteration of groundwater flow. Those secondary concerns, as outlined in the introduction, will be controlled through appropriate attention to the two primary effects. Procedures for conducting this design assessment process are described in the following subsections.

5.1 STREAM TEMPERATURE DEPRESSION

The potential effects of stream surface water temperature depression must be assessed for all environmentally sensitive streams. Each stream identified as a fish habitat is considered environmentally sensitive. Additional environmentally sensitive streams may be identified by project environmental groups. These may include non-fish stream aquifers that sustain proximal downstream fish overwintering areas or other special wildlife or vegetation areas. To prevent potential detrimental lowering of stream temperatures at these identified locations, pipe insulation will be specified for the construction mode.

Sections 3.0 and 4.0 present computer modeling results for various generalized stream environments. In general, these simulations show minimal effect on stream temperature and freeze-up and breakup dates except for the cases where a bare pipeline operating at 15°F was used.

Additionally, effects on stream temperature depression were investigated using a simplified convective heat transfer model. A range of stream flow rates was examined modeling stream flow over a chilled streambed segment. Results of these analyses indicated that stream temperatures were decreased by less than one degree for all flow rates examined. Details of the methodology and results of analysis are presented in Appendix A.

Application of three inches of circular pipe insulation shows that chilled pipe effects are significantly minimized and seasonal climatic conditions control the shallow thermal regime. Therefore, minimal three inches of circular pipe insulation, or equivalent R value, will be specified in the design mode for all streams identified as environmentally sensitive. Exceptions to this requirement may occur, however. Site-specific analysis may identify certain streams, such as large perennial streams, for which pipe insulation is not required to control adverse thermal effects.

5.2 ALTERATION OF GROUNDWATER FLOW

The primary concern for groundwater flow alteration is the potential for aufeis development and the consequences associated with aufeis formation. Each stream crossing is assessed to determine the potential impact of aufeis on:

- public and private roads
- TAPS pipeline and civil structures
- other adjacent private and public facilities, and
- the environment

Another major concern of groundwater flow alteration is redirection of groundwater flow to the surface which normally provides base flow to downstream fish overwintering areas.

Before an analysis of chilled pipeline effects on groundwater flow can be performed, it is necessary to characterize the occurrence and direction of groundwater flow for undisturbed conditions. Along the pipeline alignment, groundwater may occur as suprapermafrost, intrapermafrost, or subpermafrost groundwater (Cederstrom et al, 1953, Reference 6) or it may occur in totally thawed regions. The direction of groundwater flow may be characterized as recharge (vertically downward flow), discharge (vertically upward flow) and lateral flow (flow that is predominantly parallel to the land surface). The occurrence and direction of groundwater flow can be characterized for use in the following levels of analysis, using available data and applying the general principles for groundwater flow. Details of the procedures for making these characterizations are given in the report entitled, Exhibit-A Design, "Approach for Chilled Gas Pipeline Effects on Streams - Groundwater Analysis Design Considerations - Stream Crossings" (Reference 7).

5.2.1 Level I Analysis

Level I analysis is based on the Darcy Equation:

$$q = Ki \tag{5-1}$$

where
q = Darcy velocity, Ft^3/ft^2-d
k = hydraulic conductivity Ft/d
i = hydraulic gradient Ft/ft

The Darcy velocity is used to compute the unit width groundwater flow volume from the equation:

$$Q_W = qD \tag{5-2}$$

where
Q_W = unit width aquifer discharge, Ft^3/ft-d
D = depth of groundwater flow, Ft

Streams that have a combination of local hydraulic gradient and hydraulic conductivity that results in a Darcy velocity of less than 0.1 Ft^3/ft^2-d are considered nonproblematic with respect to groundwater flow, based on the following considerations:

- The volume of water diverted by the pipeline and potential frost bulb is insignificant if:

  - the blockage is in a groundwater recharge area, the volume of infiltrating water blocked may range from zero to a maximum of 0.1 Ft^3/ft^2-d times the frost bulb width. This quantity in Ft^3/ft^2-d per foot length of pipeline traversing the recharge area is expected to be negligible when averaged over the reach of the stream.

  - the blockage is in a groundwater discharge area, the volume of water intercepted by the pipe is expected to be diverted around the pipeline, so that the total volume discharging remains nearly the same. In this case, the location of the discharge affected by the pipeline may be slightly shifted upstream or downstream of the crossing.

  - the blockage is in an area where groundwater flow is lateral, the volume of flow blocked may range from zero to a maximum of 0.1 Ft^3/ft^2-d times the frost bulb depth. If insulation is used and/or the aquifer is thicker so that a lesser percentage of the flow is interupted, then the volume of flow altered becomes some percentage of the total flow as presented in Figure 5-2.

- As shown in the simulations discussed in Section 4.0, in most cases a flow rate of 0.1 Ft^3/ft^2-d is not sufficient to provide enough convective heat transfer to the surface to prevent freezing into the subsurface. Therefore, if the shallow surface aquifer is thawed deeper than the potential pipeline blockage the redirection of flow is expected to be beneath the pipeline. In other areas, the maximum aufeis produced is expected to be minor.

Included within a Level I type of analysis is a consideration of the region of groundwater flow. This analysis applies to streams located in continuous permafrost regions and streams flowing over competent bedrock or other highly impermeable units. If the area available for groundwater flow is assessed to extend less than 5 feet into the subsurface below the stream bed, special design considerations for chilled pipeline effects on groundwater flow are not required. In most instances, as indicated by the analysis presented in Sections 3.0 and 4.0, this region is expected to freeze down, placing all groundwater flow in storage until the next thaw. It is anticipated that those areas not totally frozen will be isolated islands of unfrozen soil that do not contribute significant water to nearby streams.

In those areas where adjacent facilities are less than 500 feet downstream, such as TAPS, the Dalton Highway, and other public and private facilities, the aufeis assessment procedure described in Subsection 5.4 will be employed using the conservative quantity of groundwater flow, shown above, as input, or analysis will proceed directly to Level II.

5.2.2 Level II Analysis

Streams having a combination of local stream gradient and hydraulic conductivity that results in a groundwater flow rate of greater than 0.1 Ft^3/ft^2-d require a Level II type of analysis. These groundwater flow values pose a higher potential for adverse chilled pipe effects related to groundwater flow alteration. The basis of this level of analysis is primarily groundwater flow direction. Knowing or making a reasonable judgement of the groundwater flow direction using the procedures described above, the following analyses are applied as appropriate.

Lateral Flow

Lateral groundwater flow areas exist where groundwater flow is predominantly parallel with the land surface. Typical environments include streams underlain by a relatively impermeable medium at shallow depths. This impermeable medium produces groundwater flow systems dominated by long areas of lateral groundwater flow. Examples include streams underlain by relatively impermeable permafrost, competent bedrock, and other geologic formation having a low hydraulic conductivity.

The operation of a chilled pipeline in a lateral groundwater flow area may act as a subsurface dam possibly causing a redirection of groundwater flow to the surface to form aufeis. Another impact of this blockage may be a reduction in the supply of groundwater to downstream fish streams.

An assessment of groundwater flow alteration can be made using Equations 5-1 and 5-2, and Figure 5-2. This procedure provides an estimate of the quantity of groundwater flow that may be affected by the chilled gas pipeline. The procedure for using these figures is as follows:

- o Using available data and engineering judgement, estimate subsurface conditions including:
    - Cross-sectional area through which groundwater flow is occurring. This may be thaw bulb geometry and/or geometry of permeable media.
    - Assign an average hydraulic conductivity to the porous media using representative values for the geologic formations and soil classes as reported in the literature, (Freeze and Cherry, 1979 Reference 8).
    - Assume saturated flow conditions.
- o Assume the hydraulic gradient is equal to the local topographic gradient.
- o Assume total blockage by the chilled pipeline approaches the maximum expected frost bulb size for the soil type, design climate, and construction mode.
- o Use Equation 5-1 to find the lateral groundwater flow rate.
- o Find the total unit width groundwater flow quantity using Equation 5-2.
- o Using the value from Equation 5-2, and knowing the percent of potential flow blockage from estimates of the flow region geometry and the assumption in the third bullet above, use Figure 5-1 to find the potential quantity of groundwater that may be redirected to the surface.

- Use the procedure described in Subsection 5.4 to assess the potential development of aufeis, using the computed values of groundwater flow diverted to the surface.

- Assess the potential impact to downstream water bodies as a result of the potential loss in base flow.

Recharge Flow

Recharge flow conditions exist where groundwater flow is moving vertically down from the ground surface. Typical stream environments include alluvial fans, alluvial terraces and other environments where the water table is below the bed of the stream throughout all or most of the year.

There are two basic situations that may be analyzed for chilled pipeline effects on groundwater flow in recharge areas. These two cases are:

- areas where water freely drains in a vertical downward direction beyond a depth assumed to exceed the maximum potential blockage by the pipeline and attendant frost bulb and,

- areas where the vertical downward flow of groundwater is intercepted by a unit having a lower permeability than overlying units, causing groundwater flow to be redirected parallel to this unit.

In the first case, alteration of groundwater flow is considered insignificant and therefore any stream exhibiting these characteristics will be considered to be nonproblematic with respect to chilled pipeline effects on groundwater flow.

For the second case in which flow is redirected by a lower permeability unit at shallow depth, effects are assessed in the same manner as for lateral groundwater flow areas. That is, the zone from the surface down to the lower permeability unit is assumed saturated and flow occurs laterally along this unit. With these assumptions, the procedures outlined for assessing lateral flow areas are applied.

An additional analysis may be performed for recharge areas underlain by a relatively impermeable zone at shallow depths. This analysis involves assessing the probability of the water table intersecting the pipeline. If it is highly improbable for the water table to rise to the bottom of the pipeline or the frost bulb then redirection of groundwater flow to the surface by the pipeline is highly improbable.

The method for determining the probability of the water table intersecting the pipeline or the frost bulb is based upon Figures 5-3A and 5-3B which are taken from the U.S. Bureau of Reclamations' Drainage Manual, 1978 (Reference 9). These graphs represent steady state dimensionless water table profiles for steady infiltration on a sloping ground surface underlain by a sloping impermeable unit. The surficial deposits are assumed homogeneous and isotropic in their hydraulic properties.

The procedures for determining the shape of the water table in the area of concern proceeds as follows:

- Using available data or assumptions estimate:

  I = a maximum probable infiltration rate for the summer (ft^3/ft^2-d)

  k = an average hydraulic conductivity of the surficial deposits (ft/d)

  L = length of the slope over which infiltration occurs (ft) (see Figure 5-4)

  S_s = land surface slope (ft/ft)

  S_b = slope of the impermeable unit (ft/ft)

  D_{b1} = depth to the impermeable unit at the upper end of the area (ft)

  D_{b2} = depth to the impermeable unit at the lower end of the area (ft)

- Make a cross-sectional profile of the area as shown in Figure 5-4.

- Develop a table of coordinates for h, the height of the water table above the impermeable unit and L, the distance from the top of the slope where infiltration exists as follows:

  - Find the value of $I/k\ S_b{}^2$.

  - Make a table of values for h/S_bL for various values of x/L from the appropriate graph in Figure 5-3A or 5-3B (x is the horizontal distance from the edge of the region where infiltration occurs and varies in value from 0 to L).

  - Compute corresponding values of x for the appropriate values of x/L (above), knowing L.

- Compute corresponding values of h, using the values of h/S_bL knowing S_b and L.

- Graph the water table profile on the cross-section developed using the computed values.

After the water table profile is plotted, the proposed pipeline may be located on the cross-section profile. If the pipeline location is in an area where the water table lies below the pipeline structure, then chilled pipeline effects on groundwater flow are considered nonproblematic and special design considerations are not required. Otherwise, the stream crossing will require a Level III analysis.

Discharge Areas

Groundwater discharge areas occur where groundwater exists from the groundwater flow system. Generally, groundwater discharges in topographicly low areas such as at streams, lakes and other depressions. Groundwater discharge areas may be identified by the perennial occurrence of surface waterbodies such as perennial streams, lakes and springs, various varieties of vegetation and in the arctic and subarctic, by some occurrences of aufeis.

Groundwater discharge occurs wherever the water table intersects the land surface. This intersection may be brought about by an abrupt change in hydraulic gradient, or hydraulic conductivity, gravity flow and other geologic controls. Some examples of typical groundwater discharge occurrences in arctic and subarctic regions of Alaska are shown in Figure 5-5. Any of these areas may have an associated icing potential when air temperatures are below freezing.

The primary consideration for chilled pipeline effects on groundwater flow in discharge areas is augmentation of existing aufeis development. The proposed chilled gas pipeline route has been chosen in order to avoid many aufeis occurrences; however, some areas of contact are unavoidable due to other design considerations. Therefore, an assessment of chilled pipeline effects in these areas is required. This is performed primarily to characterize the conditions causing groundwater discharge. If it is assessed that the discharge is largely a localized phenomenon, for example a spring or other point discharge, then a route realignment may be necessary to avoid the occurrence.

Discharge of water occurring on a regional scale, is more difficult to avoid. There is very little that can be done to prevent aufeis from developing in these areas; therefore, the design mode in groundwater discharge areas will incorporate techniques that control the discharging groundwater so that impacts to the environment and adjacent facilities are minimized. These special design solutions are described in Subsection 5.5.

5.2.3 Level III Analysis

After applying a Level I and II type of analysis to the stream crossing a number of streams may be identified as problematic with respect to chilled pipe effects. These streams are subject to a Level III analysis.

This third level of analysis uses computer modeling techniques for assessing chilled pipeline and groundwater flow interaction. At this level, there are two types of analyses that may be performed. The first type of analysis is based upon categorization of the remaining stream crossings and conducting computer simulations, using a generic stream crossing model that is representative of an individual category. This analysis is referred to as a Level III-A analysis. The second type of analysis is site-specific analysis using an idealized stream model that represents the site-specific conditions of a particular stream crossing and is referred to here as Level III-B analysis.

Stream categorization is employed to determine designs that will limit undesirable chilled pipeline effects on streams. This process consists of: 1) selectively grouping streams into a series of categories, 2) assessing the potential chilled pipeline effects using analyses appropriate for each category, 3) identifying streams that require special design considerations, and 4) selecting designs that will minimize potential adverse effects of the chilled gas pipeline. Stream categories are based upon the physical characteristics of a stream environment outlined in Table 5-1.

Specific input variables to the simulations that will require definition for each of the generic streams are listed in Table 5-2. The choice of specific values of each for these variables will be directed toward conservatism, both in assessing the maximum frost bulb growth and groundwater flow alteration. However, the ranges for these values will be governed by reasonable estimates for these values based upon evaluation of site-specific conditions of each stream within the category.

The generic stream crossing defined for a category serves as input to a more realistic evaluation of potential chilled pipe effects using computer simulations. First, a simulation is performed to establish undisturbed conditions representative of the category. Then, effects of chilled pipeline operation are evaluated using more appropriate design parameters . The results of the simulations are used to assess the potential impact to the environment and adjacent facilities.

Those streams identified in the Level III-A analysis as remaining problematic may be given a site-specific analysis on an individual stream basis. This analysis proceeds in a similar manner to the analysis performed for the generic stream developed for category analysis, except at this stage, site-specific values for those variables listed in Table 5-2 are used in the computer simulations.

If a particular stream crossing is found to remain problematic even after a site-specific assessment, design alternatives are investigated for minimizing the potential chilled pipeline effects. A number of design alternatives are described in Subsection 5.5. These design alternatives will be evaluated as to the most appropriate design mode for the specific location. This will be determined by reassessing the problematic stream crossing using the selected alternative design. In addition, the chosen design for all stream crossings will require evaluation with respect to compatibility with the requirement of the design for frost heave and thaw settlement.

5.3 FLOODPLAIN ALIGNMENT

Assessment methodology is developed for those areas where the chilled pipeline alignment parallels a stream for considerable distances within the floodplain of the stream. These areas include the following alignment segments:

Atigun River Flood Plain #1	MP 168.77 - 169.43
Atigun River Flood Plain #2	MP 170.0 - 170.43
Atigun River Flood Plain #3	MP 170.59 - 171.25
Dietrich River Flood Plain #1	MP 181.79 - 183.98
Dietrich River Flood Plain #2	MP 183.98 - 185.40
Dietrich River Flood Plain #3	MP 185.40 - 197.00
Middle Fork Koyukuk River Flood Plain	MP 213.80 - 214.34
Ray River Flood Plain	MP 346.84 - 347.31

Three types of floodplain alignments are delineated for the purpose of assessing chilled pipeline effects. These types are distinguished primarily on the basis of the existence and thickness of the underlying shallow aquifer, the nature of the groundwater-surface water interaction, and the properties of the material at the base of the aquifer. Generalized cross-sections of these alignments are shown in Figures 5-6, 5-7, and 5-8.

Type I alignments are underlain by shallow continuous permafrost as shown in Figure 5-6. Groundwater flow, if it occurs at all in the vicinity of the pipeline, occurs in a shallow active layer. In Type I alignment sections, groundwater flow is not expected to pose a problem because complete freeze down occurs in the winter months.

A generalized cross-section of Type II floodplain alignments is shown in Figure 5-7. These segments are underlain by continuous permafrost where the maximum depth to permafrost is 25 feet. Therefore, groundwater occurrence is limited to suprapermafrost occurrences.

Groundwater flow in Type II segments can be characterized by three general flow conditions: effluent flow, influent flow and down valley flow. Effluent flow occurs when groundwater levels in the floodplain are higher than stream stage. This condition develops due to infiltration at the surface, significant contributions from local groundwater systems and/or following a drop in river stage. Influent conditions develop during river stage increases when the water moves from the stream into the adjacent aquifer (generally referred to as bank storage). The latter groundwater flow condition occurs when groundwater levels drop below the stream bed and the primary component of groundwater flow in the floodplain alluvium is down valley, where discharge occurs in lower reaches of the river.

By considering the groundwater flow characterization above and Figure 5-7, the primary chilled pipe effects concerns for Type II alignments are: 1) a decrease in temperature of groundwater during effluent conditions, 2) a reduction of groundwater flow toward the stream due to potential blockage by the pipeline and attendant freeze bulb, 3) a decrease in bank storage due to potential blockage by the pipeline and attendant frost bulb and, 4) redirection of groundwater flow to the surface in the winter, resulting in aufeis formation. An assessment of these effects are required for each segment identified as a Type II alignment.

The methodology employed to assess the potential chilled pipeline effects for Type II alignments uses computer simulations. Each of the segments within a floodplain alignment are evaluated with respect to their hydrogeological and thermal characteristics. Using this evaluation, a conservative generic model is developed for conducting simulations of an operating chilled pipeline in this environment. Development and implementation of these simulations will be similar to those described in Section 4.0. Undisturbed conditions will be established and then chilled pipeline operation will be introduced to examine the potential physical effects. The results of this simulation are used to assess the potential chilled pipeline effects within each of the Type II segments for the floodplain alignment. Those segments identified as problematic will be reassessed with one or more of the design alternatives described in Subsection 5.5.

Type III floodplain alignments are similar in physical characteristics to Type II alignments except that permafrost is absent or located below a depth of 25 feet. A generalized cross-section of Type III alignments is depicted in Figure 5-8. Groundwater flow conditions and chilled pipeline effects are comparable to

Type II alignments. The assessment methodology used for Type III alignments is the same as for the Type II alignments. All Type II segments within the floodplain alignment are evaluated in order to develop a generic model that conservatively represents the group of segments. In this model, the lower boundary will not be permafrost but rather the base of the alluvial valley fill or other appropriate boundary. Undisturbed conditions will be simulated for the generic segments and then pipeline operation will be introduced to examine the potential chilled pipeline effects. The results of the simulation will be used to assess the potential chilled pipeline effects for each Type III segment. Those segments indicated as problematic will be reassessed with the appropriate design alternative selected from those described in Subsection 5.5.

5.4 AUFEIS

The previous sections described the methods which are used to assess the potential chilled pipe effects on groundwater flow. One result of this assessment is the potential quantity of groundwater flow that may be discharged to the surface. This section presents the methods applied to assess the potential aufeis development resulting from this discharge.

A truly quantitative prediction of aufeis development resulting from groundwater discharge is not possible because of the numerous uncertainties about the data required for such a prediction (Reference 10). However, by employing general physical principles of surface water flow and heat transfer in conjunction with engineering judgement a qualitative assessment may be performed. The results of this assessment may be used as input to other analyses to evaluate impacts on the environment and adjacent facilities. For example, the location and extent of aufeis as determined by this assessment may serve as input to the analysis of bank migration and channel scour analysis, or structure overtopping or encroachment, in order to evaluate the effects of the potential aufeis field on the environment and related facilities.

The method for estimating the location and extent of aufeis development is based on the following equations. This method requires information on:

- o Groundwater seepage
- o Surface features including stream channel characteristics and,
- o Climate conditions

Groundwater seepage information is obtained as described in the preceding sections. Groundwater flow discharging to the surface, as a result of blockage by the chilled pipe, will generate a shallow surface water stream which will freeze at some point downstream of the seepage.

Knowing the potential discharge rate of groundwater flow and surface features, including stream channel characteristics, the resulting surface flow may be determined. This shallow surface flow may be computed by Manning's equation:

$$Q = \frac{1.486}{n} wd^{5/3} \quad S^{1/2} \tag{5-3}$$

where,

n = Manning's roughness coefficient
w = the width of flow
d = depth of flow
S = the channel or land surface slope
Q = the discharge

In this assessment, Q will be determined from the analysis described in Subsection 5.2.2. The width of flow may be assumed to be the stream channel width where a well defined channel exists and the slope is as defined. Values for Manning's n are reported in the literature for numerous stream channel characteristics. By inspection, the only remaining unknown is depth of flow which can be computed from Equation 5-3.

The result from this computation serves as input to appropriate heat transfer equations to assess the distance the flow will travel before it freezes completely.

For instance, the rate at which freezing will occur may be estimated from the following equation:

$$t_f = a_1 \ln \frac{b_1 T_F + b_2}{b_1 T_o + b_2} + \frac{Ld}{\Delta H} \tag{5-7}$$

where

t_f = time for water to freeze
T_F = freezing temperature
T_o = initial discharge temperature
L = latent heat of freezing
d = depth of flow
ΔH = heat exchange coefficient at $T = T_F$
a_1, b_1, b_2 = coefficients dependant on atmospheric parameters.

Once values of T_o, T_F, L and the atmospheric parameters are defined, a_1, b_1, b_2 and ΔH can be evaluated, so that graphs of t_f versus d can be plotted. These graphs can then be used to determine the distance at which aufeis may form downstream of the discharge point, and the rate at which the aufeis field will grow. The distance can be calculated by multiplying the time to freeze value (t_f) by the velocity of the water moving downslope.

The velocity of flow (V) may be determined by another form of Manning's equation:

$$\propto - \frac{1.486}{n} R^{2/3} S^{1/2} \qquad (5\text{-}5)$$

where

V is the average velocity of flow and
R is the hydraulic radius of flow.

In order to estimate the distance in which water will freeze, climatic data are required for the analysis. Climate data are being developed for various sections of the alignment. These data will be used for the stream crossings as appropriate.

The volume of aufeis produced can be estimated by knowing the length of time that subfreezing temperatures occur for a given area along the pipeline alignment. Multiplying this number of days by the discharge rate gives the total potential volume of aufeis that may be produced. This volume can then be distributed over the area where aufeis is expected to develop knowing the topography of this area, using project survey data and available topographic maps, the thickness and general areal distribution of the aufeis field may be ascertained.

In addition to evaluating the impacts of an aufeis field developing at an assessed downstream location, an evaluation of potential aufeis impacts will be performed, assuming that the aufeis field forms at the chilled gas pipeline crossing; in other words, to assume that all freezing occurs near the point of discharge. In this way, by assessing the impact of potential aufeis accumulations both at the crossing and a reasonable distance downstream of the crossing, the two worst case aufeis scenarios will have been evaluated.

If the computed volume and extent of the potential aufeis occurrence is assessed to encroach on an adjacent facility or to pose a blockage and erosion concern for an environmentally sensitive stream, the crossing design will be re-evaluated using the appropriate design alternatives listed in Subsection 5.5.

5.5 DESIGN ALTERNATIVES

Aufeis, whether occurring as river icings, spring icings, or ground icings, is a difficult phenomenon to analyze, predict and control. Because of its significant impact on roads, drainage structures, mechanical and civil facilities, and stream channels, due to both the physical presence of the ice and to resultant flood flows over the ice, serious design considerations are warranted. Thorough assessment of each stream crossing and selection of appropriate measures to minimize the magnitude of the potential icing provides a means to prevent or, to avoid the icing problem rather than trying to control it. Presented below are methods available for avoiding aufeis problems and, alternatively, methods available for controlling aufeis occurrences where unavoidable.

The primary singular design alternative for problematic streams is the use of pipe insulation to limit frost bulb size and therefore reduce groundwater blockage and diversion. As indicated in Sections 3.0 and 4.0, 3 inches of pipe insulation significantly reduces the thermal effects of the chilled pipeline and reduces the growth of the frost bulb. The procedures described in the preceding subsections and shown graphically in Figure 5-1 will be used to assess the acceptibility of the insulation in minimizing the chilled pipe effects. Final selection of the insulation thickness and thermal properties will depend on these analyses in conjunction with other project studies on frost heave design, thaw mitigative design, insulation materials testing, and constructibility.

If pipe insulation is assessed to be inadequate for minimizing the chilled pipe effects, then the following additional alternatives will be evaluated.

- Use of deeper burial to move the pipeline out of the groundwater flow field or reduce blockage;
- Increase in the transmissive properties of the ditch backfill to accommodate the flow;
- Installation of subsurface drains to transmit the interrupted flow past the pipeline;
- Use of an aerial crossing to avoid the problem; and
- Reroute of the pipeline to a less problematic area.

Figure 5-9 shows three scenarios in which deeper burial of the pipeline may effectively reduce the blockage of groundwater flow. Streams underlain by permafrost or bedrock at shallow depths, or at which the hydraulic conductivity of the underlying soil decreases with depth, may be considered for application of this design solution. The cost effectiveness and constructibility of this alternative will be evaluated with other possible solutions.

Another design alternative involves backfilling the ditch with materials that increase the effective transmissivity of the area around the pipeline. The required hydraulic conductivity of the ditch backfill material can be calculated as shown in Figure 5-10. This solution may be effective if the hydraulic conductivity of the ditch backfill material does not have to be significantly higher than the native soil to accommodate the groundwater flow affected by the chilled pipeline structure. In addition, select backfill materials would have to be readily available and of reasonable cost. 5

A design alternative that may be evaluated for problematic stream crossings, especially those exhibiting historic aufeis occurrences (indicating a groundwater discharge flow component) is the use of a subsurface drainage system. This method involves the installation of perforated drain pipes perpendicular to the pipe ditch and parallel with the stream flow to increase the groundwater transmissivity above the pipe, thereby minimizing the interruption to the lateral component of groundwater flow. 6

The number of pipe drains to be installed depends upon the extent of the saturated areas and the drain spacing. The drain spacing may be determined using numerical modeling techniques. As shown in Figure 5-1, the groundwater flow blocked by the chilled pipeline has to be accommodated by the pipe drain. The drain spacing that will be used is determined by the radius of influence below the pipe drain. The radius of influence is the distance from the center of the pipe drain measured vertically down to the zone of groundwater flow unaffected by the pipe drain. The lateral spacing between drains will be twice this distance. Specific configurations will be developed for those streams where drain pipes are to be used.

The evaluation of an aerial crossing or a minor reroute is dependent on cost and constructibility considerations in conjunction with overall design requirement. Use of either of these solutions would depend on site-specific conditions and may be the only viable design alternative at some stream crossing locations.

In those areas where aufeis is anticipated to develop, or unforeseen circumstances result in the development of aufeis during operation, a number of icing control methods are available. These include:

<u>Steaming</u> - This may be employed to melt an aufeis buildup on a periodic basis to prevent the icing from growing too large, such as to pose a hazard to the adjacent facilities.

<u>Hessian cloth dams</u> - This method may be used to control the location of the icing. The cloth is stretched across the path of water flow in order to intercept the flow and start an icing

buildup at the cloth. As water accumulates at the cloth and freezes, an ice dam is generated resulting in a buildup of ice from the cloth in the upstream direction. This control measure is useful in preventing aufeis encroachment upon nearby facilities. This method may also be used to control the buildup of the ice so that a more uniform buildup is created allowing a faster thaw in the spring.

Frost belts - Controlled discharge of groundwater may be provided by frost belts. These zones may be constructed in some areas by building snow fences which cause a pile up of snow on one side and significantly reduce the accumulation of snow on the other side. Where the snow is thin or absent, freezing will occur to depths sufficient to cause a subsurface ice dam. This dam will redirect groundwater flow to the surface at selected areas where aufeis formation will not adversely impact the environment or adjacent facilities.

Subsurface Drainage - The location of aufeis development may be controlled by installing subsurface pipe drains. These drains could be used to keep groundwater flow from surfacing at undesirable locations and directing the discharge to less sensitive areas.

Surface Drainage - In areas of historic aufeis development or where aufeis is anticipated to develop, various surface drainage control measures may be implemented. These measures are selected to control the erosive effects of flood flow over aufeis accumulations. The measures include upgrading drainage structures, use of perched culverts, providing heating capabilities for drainage structures, and upgrading or constructing protective measures to limit erosion.

Each of these aufeis control measures will be evaluated on a site specific basis. In some cases the control measure may be incorporated into the design and in other cases the site may be identified as a potentially problematic area that is to be monitored for aufeis occurrence, so that corrective measures can be applied in a timely manner.

6.0 TABLES

TABLE 3-1

SOIL, WATER AND INSULATION THERMAL PROPERTIES FOR EPR RUNS

MATERIAL	W	γ_d	S	C_f	C_u	K_f	K_u	HFUS*	ALP	GAM
Water	--	---	---	31	62	1.3	0.4	9000	0.01	1.0
Granular Backfill	25	100	100	29	42	2.0	1.2	3700	0.1	1.0
Native Gravel	20	110	100	29	40	2.3	1.4	3100	0.1	1.0
48" Pipe and 3" Insulation	--	---	---	0.1	0.1	0.371	0.371	0.1	0.1	0.1
48" Pipe and 5" Insulation	--	---	---	0.1	0.1	0.231	0.231	0.1	0.1	1.0

W = Moisture (%)

γ_d = Dry Density (pcf)

S = Saturation (%)

C_f = Frozen Heat Capacity (Btu/cf-°F)

C_u = Unfrozen Heat Capacity (Btu/cf-°F)

K_f = Frozen Thermal Conductivity (Btu/ft-hr-°F)

K_u = Unfrozen Thermal Conductivity (Btu/ft-hr-°F)

HFUS = Heat of Fusion (Btu/cf)

ALP = Unfrozen Moisture Parameter (°F)

GAM = Unfrozen Moisture Parameter

*The EPR model requires input for the total extractable latent heat (HFUS) and for the parameters that govern the extraction of this latent heat as a function of temperature below 32°F (ALP and GAM).

TABLE 3-2
METEOROLOGICAL INPUT DATA FOR EPR RUNS

CLIMATIC PARAMETER	TIME (DAYS) 0.0	30.4	60.8	91.3	111.5	121.7	152.1	182.5	212.9	243.4	273.8	304.2	310	315.0	334.6
1.	1834	1643	1200	731	*	309	95	21	54	238	692	1257	*	*	1652
2.	58.9	60.8	55.5	44.5	*	25.7	2.8	-9.3	-11.7	-3.6	8.6	29.8	*	*	47.5
3.	7.0	6.5	6.1	6.1	*	5.4	3.9	3.2	2.9	3.9	5.1	6.5	*	*	7.7
4.	0.73	0.75	0.78	0.75	*	0.80	0.68	0.70	0.60	0.64	0.60	0.67	*	*	0.70
5.	196	206	175	75	0	0	0	0	0	0	0	0	*	0	93
6.	0	0	0	0	0	0.6	1.2	1.6	1.8	1.8	1.7	1.4	*	0	0
7.	0	0	0	0	0	0.106	0.140	0.152	0.180	0.190	0.190	0.245	0.245	*	0

1. = Solar radiation, in Btu/day-ft²
2. = Air temperature, in °F
3. = Wind speed, in MPH
4. = Cloud cover, as a fractional amount
5. = Evaporation rate, in Btu/day-ft²
6. = Snow depth, in feet
7. = Snow density, in gm/cc

Surface shortwave emissivity (absorptivity) = 0.82
Snow shortwave emissivity (absorptivity) = 0.30
Surface longwave emissivity = 0.90
Snow longwave emissivity = 0.95
Surface roughness, in feet = 0.50
Snow roughness, in feet = 0.05
Clear sky incoming radiation in Btu/hr-ft² = 40.0
Dimensionless factor that allows variation in the evaporation rate from grid point to grid point = 1.0
Dimensionless factor that allows variation in the snow depth from grid point to grid point = **
Dimensionless factor that allows variation in the snow density from grid interval to grid interval = 1.0

*Values are interpolated by EPR program.

**This factor was varied to generate the desired initial soil temperature:

Non-permafrost w/12-inch surface water:	0.18	Permafrost w/12-inch surface water:	0.13
Non-permafrost without surface water:	0.15	Permafrost without surface water:	0.11

TABLE 3-3

FROST BULB GROWTH BELOW BOTTOM OF PIPE

RUN NO.	RUN DESCRIPTION	FROST BULB DEPTH BY END OF YEAR 5	ADDITIONAL ANALYSES
	** With 12" Surface Water Depth **		
JV0112	4' Cover, No Insulation	20.90 Feet	
JV0120	4' Cover, 3" Insulation	2.35 Feet	3.60'/Yr. 10 (JV0133)
JV0114	4' Cover, 5" Insulation	0.43 Feet	0.65'/Yr. 10 (JV0132)
JV0170	8' Cover, 3" Insulation	2.49 Feet	4.11'/Yr. 9 (JV0221)
JV 0168	8' Cover, 5" Insulation	0.49 Feet	
	** With No Surface Water **		
JV0310	4' Cover, 3" Insulation	2.14 Feet	
JV0295	8' Cover, 3" Insulation	3.99 Feet	

TABLE 3-4

FREEZE AND THAW DATES FOR STREAM BOTTOM DIRECTLY ABOVE PIPE

RUN NO.	RUN DESCRIPTION	FREEZE DATE	THAW DATE
	** NON-PERMAFROST ENVIRONMENT - 12" SURFACE WATER**		
JV0107	Control (No Pipe)	Day 1652	Day 1797
JV0112	4' Cover, No Insulation	1570 (82 Days earlier)	1820 (23 days later)
JV0120	4' Cover, 3" Insulation	1646 (6 Days earlier)	1798 (1 day later)
JV0114	4' Cover, 5" Insulation	1647 (5 Days earlier)	1798 (1 day later)
JV0170	8' Cover, 3" Insulation	1647 (5 Days earlier)	1797
JV0168	8' Cover, 5" Insulation	1648 (4 Days earlier)	1797
	** PERMAFROST ENVIRONMENT - 12" SURFACE WATER**		
JV0290	Control (No Pipe)	1623	1798
JV0291	4' Cover, 3" Insulation	1623	1800 (2 days later)
JV0292	8' Cover, 3" Insulation	1625 (2 days later)	1800 (2 days later)

1. Values in parentheses denote the deviation from the control run.

2. Dates are derived from straight line interpolation between data points of 32°F isotherm depth vs. time plots of EPR output, 5th year.

TABLE 3-5

TEMPERATURE (°F) OF STREAM BOTTOM DIRECTLY ABOVE PIPE UNDER 12" SURFACE WATER

		NON-PERMAFROST						PERMAFROST		
DAY	MONTHS AFTER START	JV0107 CONTROL (NO PIPE)	JV0112 4' Cov. 0" Ins.	JV0120 4' Cov. 3" Ins.	JV0114 4' Cov. 5" Ins.	JV0170 8' Cov. 3" Ins.	JV0168 8' Cov. 5" Ins.	JV0290 CONTROL (NO PIPE)	JV0291 4' Cov. 3" Ins.	JV0292 8' Cov. 3" Ins.
1277	42	32.81	14.98 (-17.8)	32.41 (-0.4)	32.50 (-0.3)	32.53 (-0.3)	32.58 (-0.3)	31.24	31.25 (0.0)	31.46 (+0.2)
1308	43	30.76	10.10 (-20.7)	29.30 (-1.5)	29.59 (-1.2)	29.71 (-1.1)	29.90 (-0.9)	25.23	25.29 (+0.1)	25.34 (+0.1)
1338	44	27.58	9.91 (-17.7)	26.45 (-1.1)	26.65 (-0.9)	26.87 (-0.7)	26.99 (-0.6)	22.15	19.38 (-2.8)	22.11 (0.0)
1368	45	27.19	12.70 (-14.5)	26.35 (-0.8)	26.54 (-0.7)	26.54 (-0.7)	26.64 (-0.6)	21.47	15.80 (-5.7)	17.43 (-4.0)
1399	46	29.82	19.50 (-10.3)	28.92 (-0.9)	29.56 (-0.3)	29.62 (-0.2)	29.68 (-0.1)	25.13	22.89 (-2.2)	23.32 (-1.8)
1429	47	30.94	29.66 (-1.3)	30.95 (0.0)	31.03 (+0.1)	31.05 (+0.1)	31.07 (+0.1)	30.76	30.77 (0.0)	30.81 (0.0)
1460	48	38.45	32.32 (-6.1)	38.12 (-0.3)	38.35 (-0.1)	37.73 (-0.7)	37.72 (-0.7)	37.77	37.19 (-0.6)	37.08 (-0.7)
1490	49	44.62	36.76 (-7.9)	44.09 (-0.5)	44.44 (-0.2)	44.61 (0.0)	44.65 (0.0)	43.84	43.34 (-0.5)	43.16 (-0.7)
1520	50	47.18	36.76 (-10.4)	44.25 (-2.9)	44.65 (-2.5)	45.09 (-2.1)	45.17 (-2.0)	44.03	43.61 (-0.4)	43.68 (-0.4)
1551	51	43.30	33.51 (-9.8)	39.65 (-3.7)	40.46 (-2.8)	41.48 (-1.8)	42.00 (-1.3)	39.33	38.98 (-0.4)	39.07 (-0.3)
1581	52	35.19	31.57 (-3.6)	32.72 (-2.5)	33.52 (-1.7)	33.62 (-1.6)	34.04 (-1.2)	32.60	32.47 (-0.1)	32.52 (-0.1)
1612	53	33.52	28.41 (-5.1)	32.24 (-1.3)	32.46 (-1.1)	32.52 (-1.0)	32.76 (-0.8)	32.22	32.24 (0.0)	32.23 (0.0)

NOTE:

1. Values in parentheses denote the deviation from the control run.

TABLE 3-6

TEMPERATURE (°F) OF STREAM BOTTOM AT THREE LOCATIONS FOR EPR RUN JV0120

DAY	MONTHS AFTER START OF RUN	CONTROL JV0107 (NO PIPE)	AT PIPE CENTERLINE	11 FEET FROM PIPE	19 FEET FROM PIPE
1277	42	32.81	32.41 (-0.4)	32.62 (-0.2)	32.74 (-0.1)
1308	43	30.76	29.30 (-1.5	29.87 (-0.9)	30.30 (-0.5)
1338	44	27.58	26.45 (-1.1)	26.94 (-0.6)	27.31 (-0.3)
1368	45	27.19	26.35 (-0.8)	26.71 (-0.5)	26.94 (-0.3)
1399	46	29.82	28.92 (-0.9)	29.63 (-0.2)	29.71 (-0.1)
1429	47	30.94	30.95 (0)	31.14 (+0.2)	31.19 (+0.2)
1460	48	38.45	38.12 (-0.3)	38.21 (-0.3)	38.22 (-0.2)
1490	49	44.62	44.09 (-0.5)	44.39 (-0.2)	44.42 (-0.2)
1520	50	47.18	44.25 (-2.9)	45.39 (-1.8)	46.14 (-1.0)
1551	51	43.30	39.65 (-3.7)	41.98 (-1.3)	42.70 (-0.6)
1581	52	35.19	32.72 (-2.5)	33.19 (-1.0)	34.82 (-0.4)
1612	53	33.52	32.24 (-1.3)	32.82 (-0.7)	33.15 (-0.4)

NOTE:

1. Values in parentheses denote the deviation from the control run.

TABLE 3-7

TEMPERATURE (°F) OF GROUND SURFACE DIRECTLY ABOVE PIPE, NO SURFACE WATER

		NON-PERMAFROST			PERMAFROST		
DAY	MONTHS AFTER START OF RUN	JV0293 CONTROL (NO PIPE)	JV0310 4' COVER 3" INSULATION	JV0295 8' COVER 3" INSULATION	JV0289 CONTROL (NO PIPE)	JV0307 4' COVER 3" INSULATION	JV0308 8' COVER 3" INSULATION
1277	42	26.14	25.16 (-1.0)	27.01 (+0.9)	19.62	19.51 (-0.1)	19.55 (-0.1)
1308	43	20.87	19.57 (-1.3)	21.42 (+0.6)	12.86	9.86 (-3.0)	12.66 (-0.2)
1338	44	19.22	15.90 (-3.3)	19.42 (+0.2)	12.02	7.24 (-4.8)	10.70 (-1.3)
1368	45	21.35	17.91 (-3.4)	21.44 (+0.1)	14.59	10.59 (-4.0)	11.59 (-3.0)
1399	46	27.86	26.21 (-1.7)	27.78 (-0.1)	24.25	23.20 (-1.1)	23.25 (-1.0)
1429	47	48.53	48.50 (0.0)	48.80 (+0.3)	48.44	48.43 (0.0)	48.43 (0.0)
1460	48	60.10	60.08 (0.0)	60.25 (+0.2)	60.04	60.03 (0.0)	60.05 (0.0)
1490	49	61.59	61.71 (+0.1)	61.67 (+0.1)	61.55	61.65 (+0.1)	61.55 (0.0)
1520	50	55.51	55.49 (0.0)	55.36 (-0.2)	55.33	55.46 (+0.1)	55.33 (0.0)
1551	51	43.70	43.54 (-0.2)	43.40 (-0.3)	43.47	43.50 (0.0)	43.45 (0.0)
1581	52	31.81	31.79 (0.0)	31.87 (+0.1)	30.95	30.93 (0.0)	30.94 (0.0)
1612	53	29.83	29.07 (-0.8)	29.95 (+0.1)	25.42	25.42 (0.0)	25.47 (0.0)

NOTE:

1. Values in parentheses denote the deviation from the control run.

TABLE 4-1

GEOTHERMAL PROPERTIES ASSIGNED TO ZONES SHOWN IN FIGURE 4-3

Zone	K_u	K_f	C_u	C_f	n_u	n_f	L_a
1	33.6	55.2	40.0	29.0	0.34	0	3100
2	9.6	31.2	62.0	31.0	1	0	9000
3	28.8	48.0	42.0	29.0	0.41	0	3700
4	5.544 (8.904)+	5.544 (8.904)+	2.4	2.4	0	0	0.1
5	5.544 (8.904)+	5.544 (8.904)+	1E30*	1E30*	0	0	0.1

K_u thermal conductivity of thawed material, Btu/(ft-day-deg F)

K_f thermal conductivity of frozen material, Btu/(ft-day-deg F)

C_u volumetric specific heat of thawed material, Btu/(ft³-deg F)

C_f volumetric specific heat of frozen material, Btu/(ft³-deg F)

n_u porosity of thawed material, dimensionless

n_f porosity of frozen material, dimensionless

L_a total extractable latent heat of fusion, Btu/ft³

* These values are used to hold the pipe temperature constant.

\+ Effective thermal conductance of the pipe plus 5" circular insulation. Value in parenthesis is for 3" insulation. Effective conductance is based on insulation conductivity of 0.36 Btu/ft-day-deg F.

TABLE 4-2
CLIMATIC DATA INPUT

Parameters

Months	1	2	3	4	5	6	7	8	9	10	11
July 1	0	1834	58.9	7	196	0	0	0.730	0	188.05	61.8
August 1	30.4	1643	60.8	6.5	206	0	0	0.750	0	174.94	63.0
September 1	60.8	1200	55.5	6.1	175	0	0	0.780	0	164.26	56.3
October 1	91.3	731	44.5	6.1	75	0	0	0.750	0	164.66	43.9
October 20	111.5	473	35.0	5.7	0	0	0	0.780	0	153.96	34.1
November 1	121.7	309	25.7	5.4	0	0.106	0.108	0.800	0.444	3.87	19.9
December 1	152.1	95	2.8	3.9	0	0.140	0.216	0.680	0.773	3.35	- 3.9
January 1	182.5	21	- 9.3	3.2	0	0.152	0.288	0.700	0.912	2.95	-14.9
February 1	212.9	54	-11.7	2.9	0	0.180	0.324	0.600	1.279	3.61	-17.7
March 1	243.4	238	- 3.6	3.9	0	0.190	0.324	0.640	1.426	4.05	- 8.6
April	273.8	692	8.6	5.1	0	0.190	0.306	0.600	1.426	4.35	- 4.5
May 1	304.2	1257	29.8	6.5	0	0.245	0.252	0.670	2.369	8.4	26.6
May 6	310.0	1335	33.5	6.7	0	0.245	0.121	0.675	2.369	15.88	30.3
May 11	315.0	1400	36.2	6.9	0	0.206	0	0.680	1.675	186.14	39.0
June	334.6	1652	47.5	7.7	93	0	0	0.700	0	206.45	50.2

1 = Time, days
2 = Solar radiation, in equivalent Btu/day-ft²
3 = Air temperature, in °F
4 = Wind speed, in MPH
5 = Evaporation rate, in equivalent Btu/day-ft²
6 = Snow density (gm/cc)
7 = Snow depth, in feet
8 = Cloud cover, as a fractional amount
9 = Snow thermal conductivity, Btu/day-ft²-°F
10 = Coefficient of Heat transfer, Btu/day-ft²-°F
11 = Effective air temperature, °F

Surface shortwave emissivity (absorptivity) = 0.82
Snow shortwave emissivity (absorptivity) = 0.30
Surface longwave emissivity = 0.90
Snow longwave emissivity = 0.95
Surface roughness, in feet = 0.50
Snow roughness, in feet = 0.05

Note: The atmospheric simulator employs the computations given in Miller (1976) and Wheeler (1973) to compute the values for the coefficient of heat transfer and effective air temperature.

TABLE 4-3

SUMMARY OF PORFLOW-F SENSITIVITY ANALYSIS RESULTS

Input Conditions to Simulations	SUMMARY OF MODEL RESPONSES	
	Undisturbed Conditions	Pipeline Operation
1. Surface Water Depth		
- Varied from 0 to 5.25 feet - Static groundwater conditions - Static surface water conditions, i.e. no flow	o Temperature variations are dampened with depth due to the thermal capacity of the surface water body. Temperature variations are increasingly dampened as the surface water depth increases. o Sensitivity of temperature to variations in surface water depths are dampened with depth below the surface water body. o Large differences in subsurface temperatures are obtained for the various simulations for small differences in surface water depths, when the surface water depth is less than 2.5 feet. Lesser temperature differences are obtained for deeper water bodies. o Temperatures within the upper two feet of the surface closely correspond to atmospheric fluctuations, regardless of whether the top two feet are water or soil. o Frost penetration is significantly reduced as surface water depth increases.	o Bare pipeline operation results in significant freezing of the region around the pipe. The freeze bulb extends to a depth of approximately 22 feet below the pipe within 5 years. o Thermal effects below a shallow water body (<2.5 feet) will be affected by surface thermal fluctuations. The thermal regime within 2 feet of the surface above the pipeline will be dominated by atmospheric fluctuations. o Pipeline operation below a deep (>2.5 feet) static water body will be unaffected by atmospheric fluctuations. The surface water body will dampen the thermal effects of the atmosphere. o Circular insulation is effective in reducing the rate of frost bulb growth and size.

TABLE 4-3 (Continued)

Input Conditions to Simulations	SUMMARY OF MODEL RESPONSES: Undisturbed Conditions	SUMMARY OF MODEL RESPONSES: Pipeline Operation
2. Stream Temperature		
- Maximum stream temperature varied up to 59°F - 1 foot depth of flow	o Subsurface temperatures just below the streambed closelyfollow stream temperature variations. Temperature variations become dampened with increasingdepth below the stream.	o A chilled pipeline operating at 15°F and covered with 3 inches of insulation does not develop a large frost bulb beneath a warm stream. The frost bulb waxes and wanes with variations in stream temperature.
- Stream flow rate 1 ft/s - Static groundwater conditions	o Atmospheric fluctuations are completely masked by the stream due to the very high thermal capacity of the stream.	o A chilled pipeline operating at 15°F below a cold stream and covered by 3 inches of insulation will develop a frost bulb. The total thermal energy delivered to the area around the pipe by a cold stream is not sufficient for reducing the frost bulb growth.
3. Groundwater Flow Direction		
a. Groundwater Recharge - Flow rate varied from 0.1 ft^3/ft^2-d to 1.0 ft^3/ft^2-d - Surface temperature maintained at 33°F	o Ground temperatures are maintained at the incoming groundwater temperature. o Ground temperature fluctuations will closely approximate infiltrating water temperature fluctuations.	o An operating bare chilled pipeline will produce thermal effects in a groundwater recharge area similar to the effects produced for static groundwater and stream conditions. o Thermal effects produced by the chilled pipeline are relatively unaffected by increases in recharge rates. However, variations in incoming groundwater temperature may be important in reducing the growth of the attendant freeze bulb.

TABLE 4-3 (Continued)

Input Conditions to Simulations	SUMMARY OF MODEL RESPONSES: Undisturbed Conditions	SUMMARY OF MODEL RESPONSES: Pipeline Operation
		o Because the pipeline thermal effects are similar to those effects for static conditions, circular insulation is expected to be a design solution for reducing both the temperature variations and frost bulb growth.
b. Groundwater Discharge		
- Flow rate varied from 0.01 ft^3/ft^2-d to 5 ft^2/ft^2-d - Incoming groundwater temperature varied from 33°F to 40°F	o Above a discharge rate of 0.5 ft^3/ft^2-d, groundwater temperatures are maintained at the incoming temperature. Temperature variations increase because of climatic fluctuations for discharges below this rate.	o An operating bare chilled pipeline will produce thermal effects in a groundwater discharge area that are similar to the effects produced for static groundwater and stream conditions. Convective heat transfer toward the pipe is expected to retard the freeze bulb growth rate, depending upon the groundwater discharge rate and incoming groundwater temperature.
- Static, 1 foot surface water body	o Convective heat transfer by groundwater discharge can prevent freezing at the surface. For an incoming groundwater temperature of 33°F and simulated climatic conditions used here, 0.5 ft^3/ft^2-d provides sufficient convective heat transfer in these simulations.	o Circular pipe insulation is expected to be a design solution for thermal effects. (See above reasoning for recharge conditions.)
c. Lateral Flow		
- Flow rate varied from 0 to 5 ft^3/ft^2-d - Incoming groundwater temperature is varied from 33°F to 40°F	o Temperature of soil most sensitive to low groundwater flow rates. o Under simulated conditions climatic fluctuations are dampened by the presence of flowing groundwater. Thermal effects induced by the climate are dampened with depth.	o The thermal capacitance of the 33°F lateral groundwater flow is not sufficient to reduce the growth of the frost bulb around the chilled bare pipeline in these simulations. Thermal effects are similar to those effects produced using static groundwater and stream flow conditions.

TABLE 4-3 (Continued)

Input Conditions to Simulations	SUMMARY OF MODEL RESPONSES: Undisturbed Conditions	SUMMARY OF MODEL RESPONSES: Pipeline Operation
- Static, 1 foot deep surface water body	o Frost penetration may be affected by the rate and temperature of lateral groundwater flow.	o Groundwater flow may be diverted to the surface by the chilled pipeline and attendant frost bulb. o Application of circular pipe insulation is an effective design solution for decreasing temperature alteration and frost bulb growth around the chilled pipeline. o An increase in the incoming groundwater temperature to 40°F results in a significant increase in the thermal capacity lateral flow. Simulations of an insulated pipeline (3") and a flow rate of 1 ft^3/ft^2-d show that a freeze bulb does not develop within five years of operation.
4. Hydraulic Conductivity Variations		
a. Increase with depth - Lateral groundwater flow increases from 0.1 ft^3/ft^2-d to 5.0 ft^3/ft^2-d - Incoming groundwater temperature is 33°F - Static, 1 foot surface water body	o Temperature effects and frost penetration are similar to the effects shown for the lateral flow case having groundwater flow equal to flow in the upper aquifer unit.	o Although chilled pipeline operation was not included, the effects are expected to be similar to those shown for the lateral flow having a flow equal to that in the upper aquifer unit. Most redirected groundwater flow is expected to be accommodated by the lower aquifer unit, when freezing is initiated at the surface.

TABLE 4-3 (Continued)

Input Conditions to Simulations	SUMMARY OF MODEL RESPONSES: Undisturbed Conditions	SUMMARY OF MODEL RESPONSES: Pipeline Operation
b. Decreases with depth - Lateral groundwater flow of 1 ft^3/ft^2-d decreasing to 0 at 17.5 feet below the surface water body - Incoming groundwater temperature is 33°F - Static, 1 foot surface water body	o Temperature profiles and frost penetration are similar to the profiles obtained for thelateral flow having flow equalto the flow in the upper aquifer unit.	o Chilled pipeline effects are similar to the effects shown for the homogeneous case. This simulation indicates that temperature, ice formation and groundwater flow are not sensitive to aquifer thicknesses greater than 17.5 feet for the pipeline mode employed.
c. Decreases in the downstream direction - Hydraulic conductivity decreases by a factor of 50 from upstream to downstream - Incoming groundwater temperature is 33°F - Static, 1 foot deep surface water body	o Groundwater flow is redirected to the surface at the contact of the units. o Groundwater flow to the surface, at the contact of the units, results in an alteration of the thermal profile as compared to the simulation for homogeneous conditions. Convective heat transfer results in a dampening of temperation variation at the contact. o Frost penetration is reduced at the contact and upstream of the contact due to convective heat transfer to the surface.	o Not examined in this study.

TABLE 5-1

PRIMARY PHYSICAL CHARACTERISTICS OF A STREAM RELATED TO POTENTIAL CHILLED PIPELINE EFFECTS

Chilled Pipeline Effect	Important Physical Characteristics	Description Terms
1. Stream Temperature Alteration	o Stream Flow Characteristics	Permanence i.e. ephermeral, perennial intermittent
		Season of Flow
	o Climate	Project Climate Segments ✓ Route, Climate Report
	o Channel Type	Straight, sinuous, meandering, anastomosing and alluvial fan
2. Groundwater Alteration	o Permafrost Occurrence	Generally Frozen, Absent, Sporadic, and Discontinuous
	o Bed Material	All RG2C designations
	o Thaw Bulb Characteristics	Depth of thaw
	o Channel Type	
	o Stream Gradient	Gradient in ft/ft
	o Groundwater Conditions	
	- Occurrence	Suprapermafrost and intrapermafrost
	- Direction	Recharge, discharge and lateral flow
	o Climate	

Answers one of my key questions

TABLE 5-2

PHYSICAL CHARACTERISTICS TO BE EVALUATED FOR DEVELOPING A GENERIC STREAM REPRESENTATIVE OF A CATEGORY

CLIMATIC INPUT
- Solar Radiation
- Air Temperature
- Wind Speed
- Evaporation Rate
- Snow Depth
- Snow Thermal Conductivity
- Cloud Cover
- Surface Properties
  - Surface solar absorptivity
  - Snow solar absorptivity
  - Surface longwave emissivity
  - Snow longwave emissivity
  - Surface roughness
  - Snow roughness

PIPELINE INPUT
- Ditch Configuration
- Pipeline Operating Temperature
- Insulation Thickness
- Ditch Backfill

GEOTHERMAL INPUT
- Boundary Conditions
- Initial Temperatures
- Thermal Conductivities
- Heat Capacities
- Latent Heats

Table 5-2 (continued)

HYDROGEOLOGICAL INPUT

- Boundary Conditions (recharge, discharge, lateral flow)
- Hydraulic Conductivity (homogeneity)
- Specific Storage
- Porosity
- Aquifer Thickness
- Stream Variables
  - Depth
  - Discharge
  - Temperature

REGION GEOMETRY

- Location of boundaries
- Spatial distribution of geothermal and hydrogeological properties

7.0 FIGURES

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MATRIX OF E. P. R. GEOTHERMAL SIMULATIONS

ENVIRONMENT	SURFACE WATER DEPTH (INCHES)	PIPELINE BURIAL DEPTH (FEET)	INSULATION THICKNESS (INCHES)	E. P. R. RUN NUMBER	E. P. R. RUN NUMBER (RESTART)
NONPERMAFROST	12	(NO PIPE)	–	JV 0107	
		4	0	JV 0112	
			3	JV 0120	JV 0133
			5	JV 0114	JV 0132
		8	3	JV 0170	JV 0221
			5	JV 0168	
	0	(NO PIPE)	–	JV 0293	
		4	3	JV 0310	
		8	3	JV 0295	
PERMAFROST	12	(NO PIPE)	–	JV 0290	
		4	3	JV 0291	
		8	3	JV 0292	
	0	(NO PIPE)	–	JV 0289	
		4	3	JV 0307	
		8	3	JV 0308	

NOTES:

1. *ALL RUNS ARE 5 YEAR SIMULATIONS.*
2. *ALL RUNS ARE BASED ON SATURATED GRAVEL NATIVE SOIL AND SATURATED GRANULAR BACKFILL.*

FIGURE 3-1

E. P. R. GRID - 1 FOOT SURFACE WATER, 4 FOOT COVER, 5 INCH INSULATION

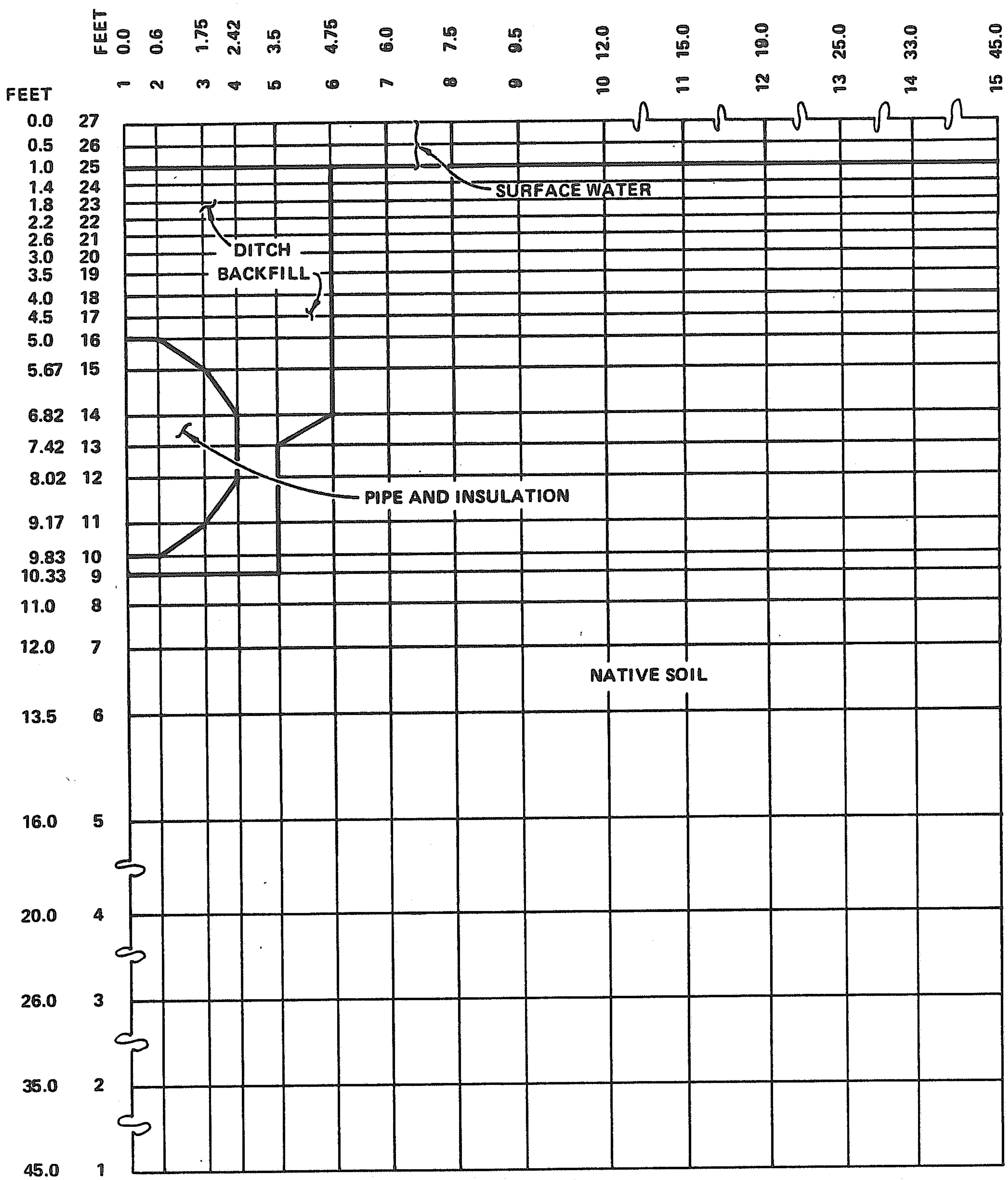
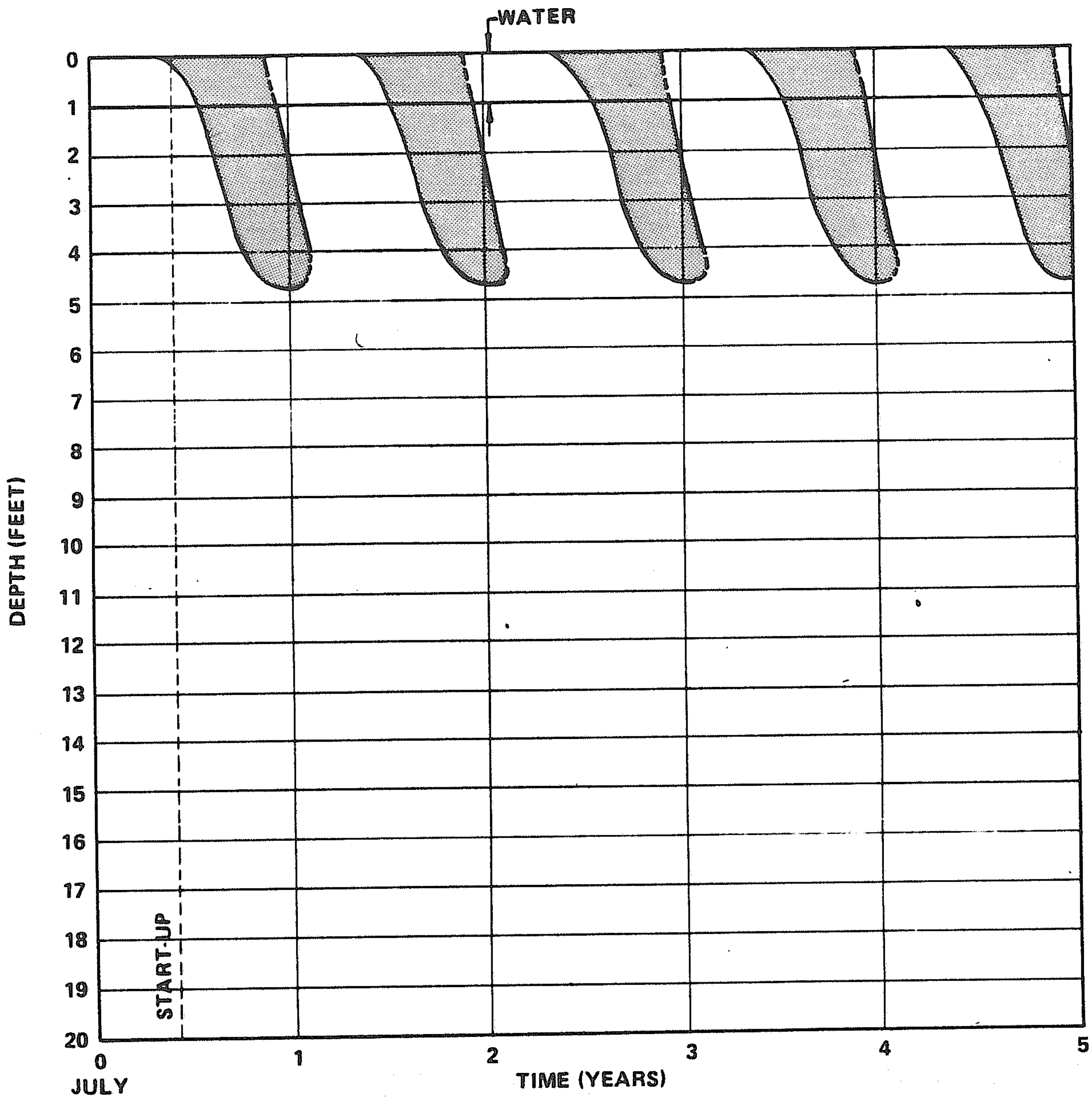


FIGURE 3-2

32° F ISOTHERM PLOT FOR E.P.R. RUN JV 0107

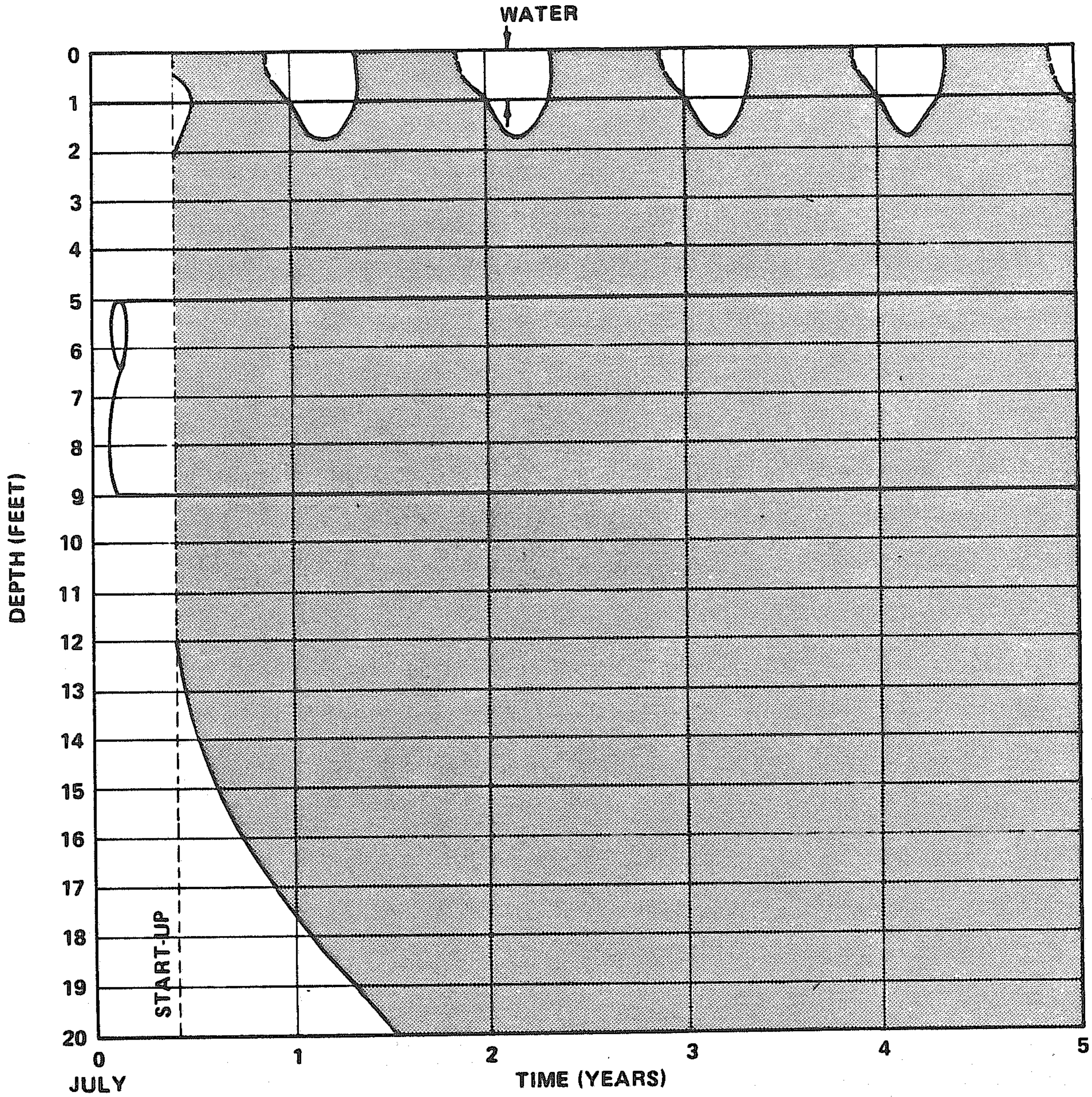


NONPERMAFROST ENVIRONMENT
12 INCHES POOLED SURFACE WATER
CONTROL RUN - NO PIPE
INITIAL ANNUAL AVERAGE SOIL
TEMP. = 34.4° F AT 9.83' DEPTH
SATURATED GRAVEL NATIVE SOIL

BELOW 32° F

FIGURE 3 - 3

32° F ISOTHERM PLOT FOR E.P.R. RUN JV 0112



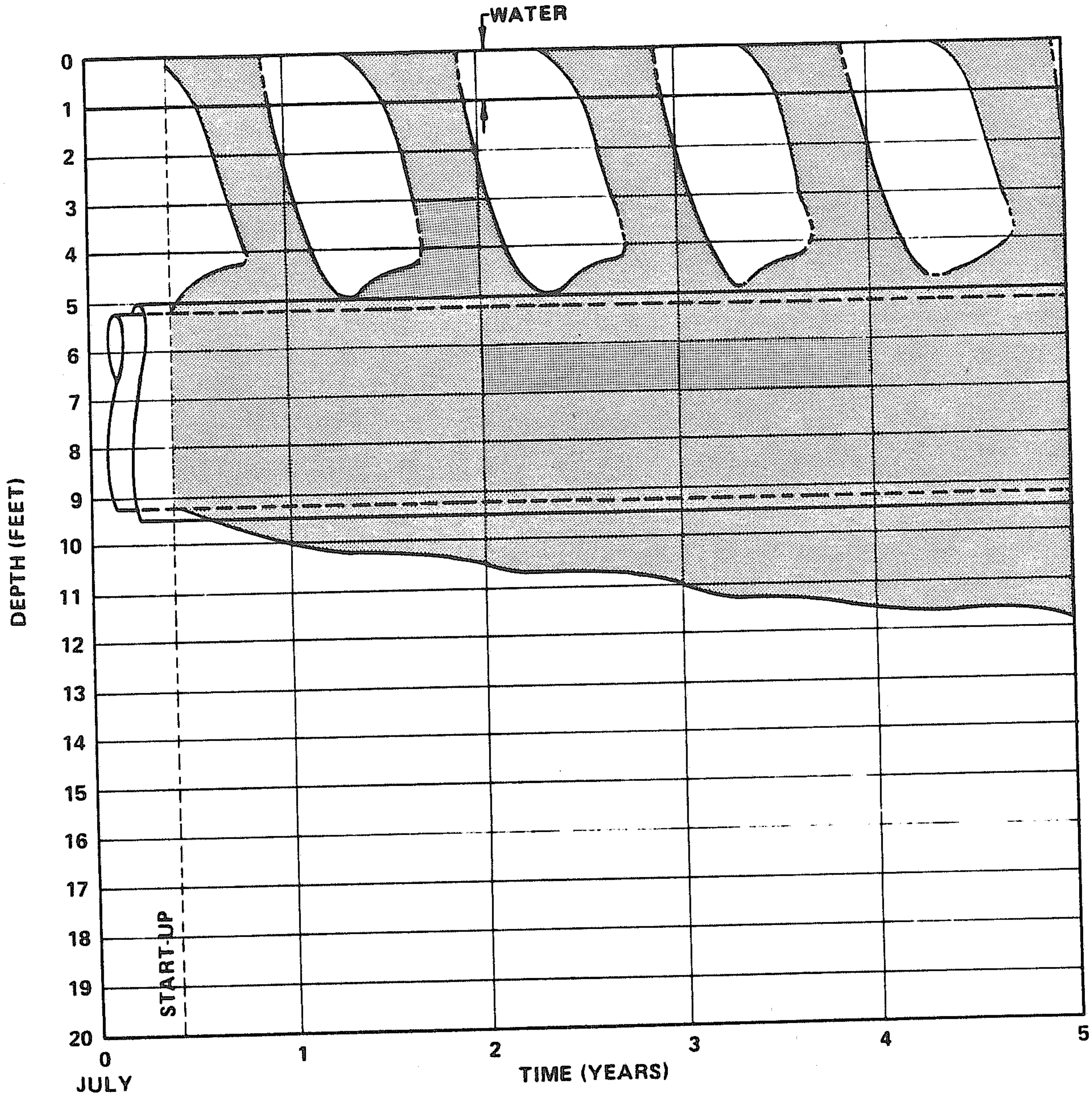
NONPERMAFROST ENVIRONMENT
12 INCHES POOLED SURFACE WATER
4 FOOT COVER DEPTH
UNINSULATED PIPE
GAS OPERATING TEMP. = 15° F
INITIAL ANNUAL AVERAGE SOIL TEMP. = 34.4° F AT 9.83' DEPTH
SATURATED GRAVEL NATIVE SOIL
SATURATED GRANULAR BACKFILL

▢ BELOW 32° F

NOTE : FROST DEPTH EXTENDS TO 30 FT. AT END OF YEAR 5, 21 FT. BELOW PIPE BOTTOM.

FIGURE 3 - 4

32° F ISOTHERM PLOT FOR E.P.R. RUN JV 0120

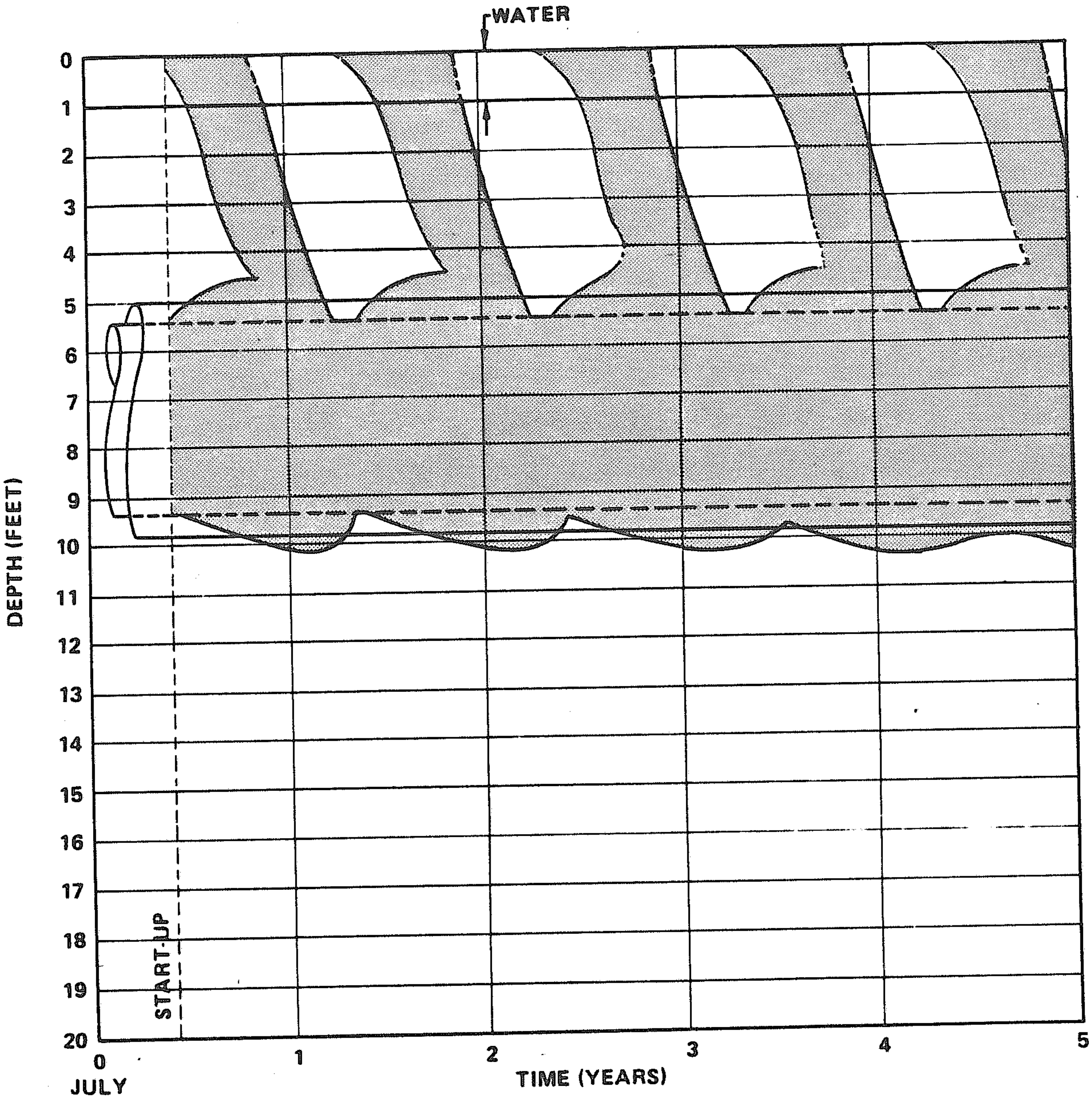


BELOW 32° F

NONPERMAFROST ENVIRONMENT
12 INCHES POOLED SURFACE WATER
4 FOOT COVER DEPTH
3 INCH PIPE INSULATION
GAS OPERATING TEMP. = 15° F
INITIAL ANNUAL AVERAGE SOIL
TEMP. = 34.4° F AT 9.83' DEPTH
SATURATED GRAVEL NATIVE SOIL
SATURATED GRANULAR BACKFILL

FIGURE 3 - 5

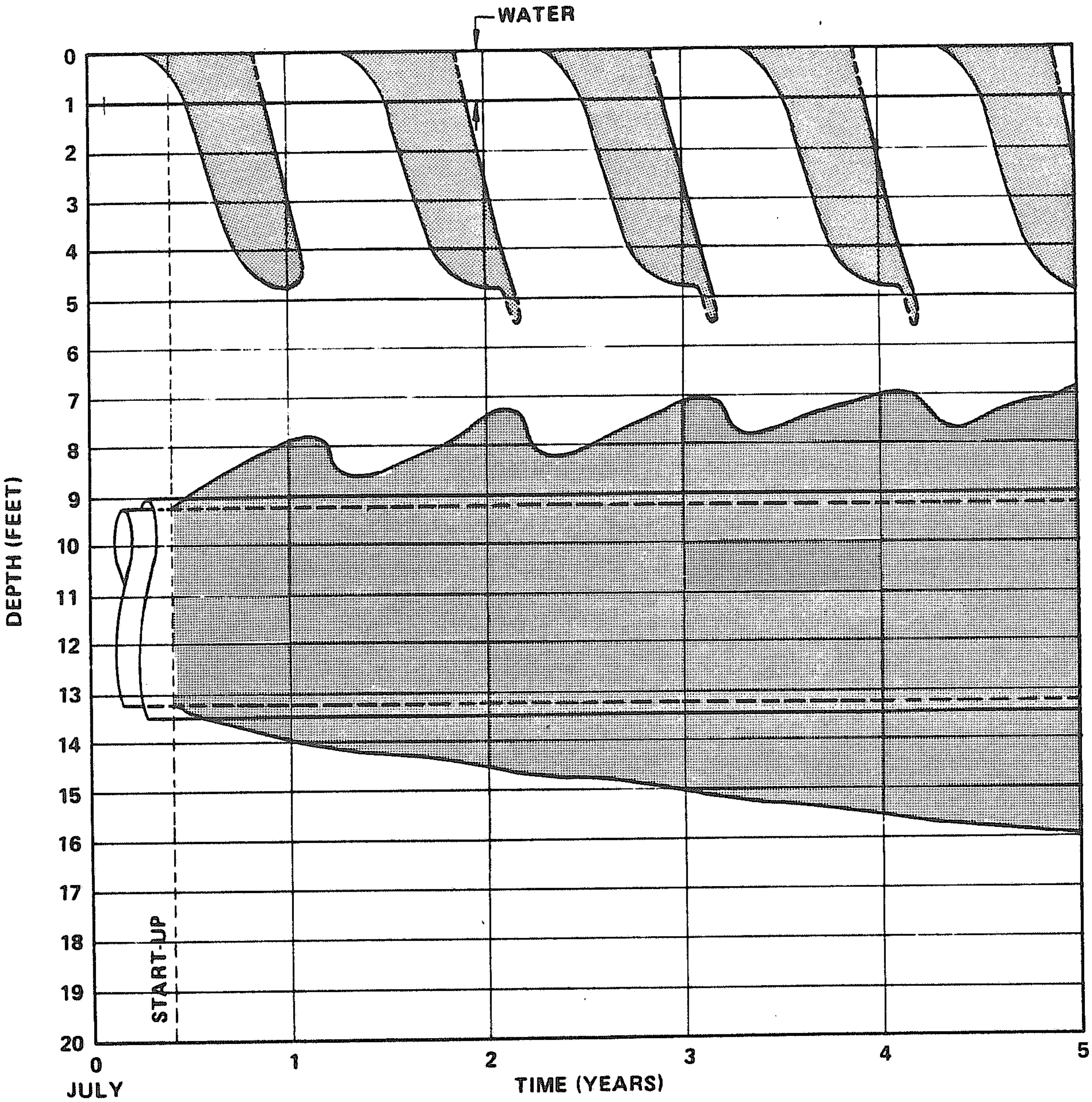
32° F ISOTHERM PLOT FOR E.P.R. RUN JV 0114



NONPERMAFROST ENVIRONMENT
12 INCHES POOLED SURFACE WATER
4 FOOT COVER DEPTH
5 INCH PIPE INSULATION
GAS OPERATING TEMP. = 15° F
INITIAL ANNUAL AVERAGE SOIL
TEMP. = 34.4° F AT 9.83' DEPTH
SATURATED GRAVEL NATIVE SOIL
SATURATED GRANULAR BACKFILL

FIGURE 3-6

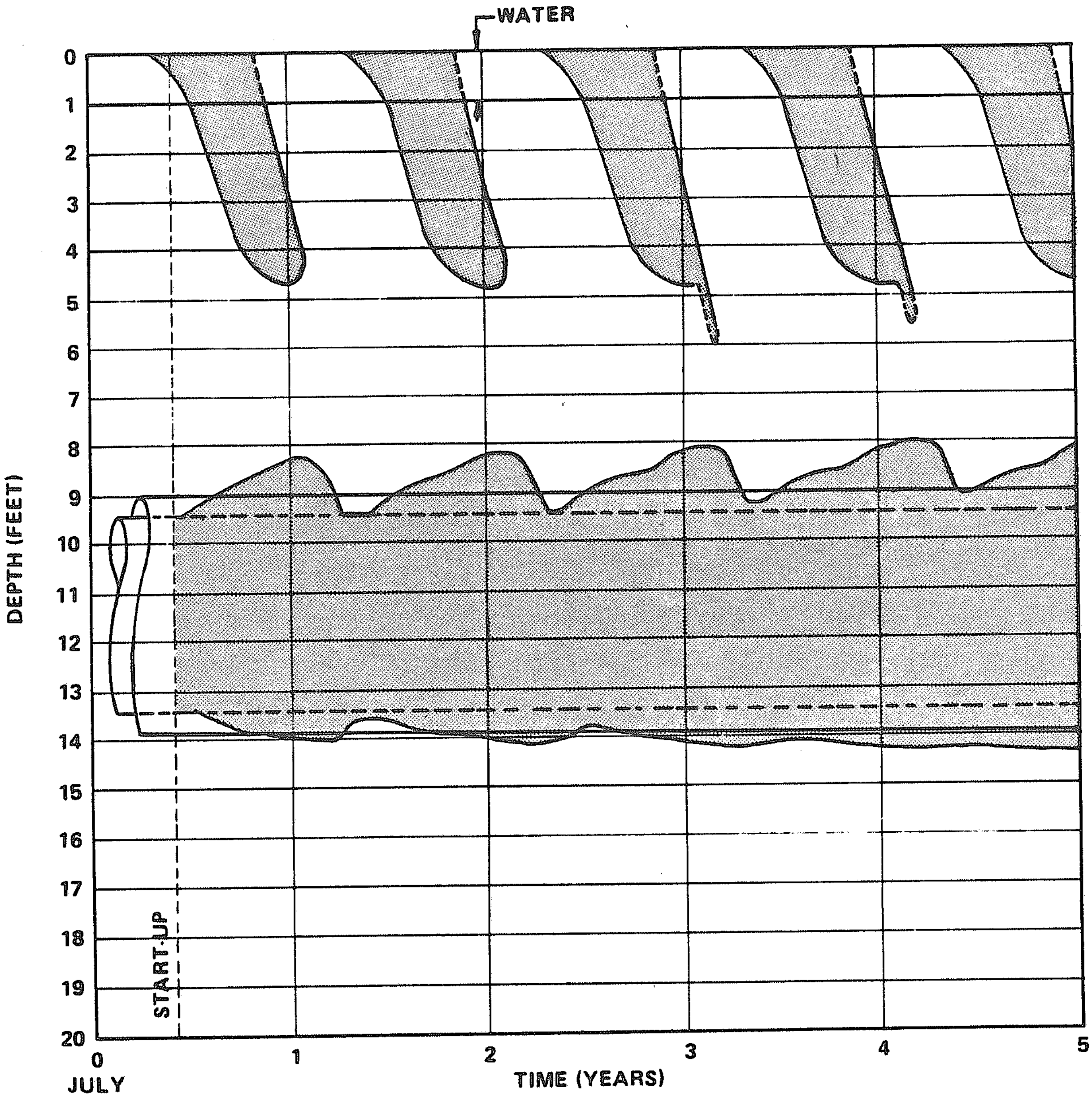
32° F ISOTHERM PLOT FOR E.P.R. RUN JV 0170



NONPERMAFROST ENVIRONMENT
12 INCHES POOLED SURFACE WATER
8 FOOT COVER DEPTH
3 INCH PIPE INSULATION
GAS OPERATING TEMP. = 15° F
INITIAL ANNUAL AVERAGE SOIL
TEMP. = 34.4° F AT 9.83' DEPTH
SATURATED GRAVEL NATIVE SOIL
SATURATED GRANULAR BACKFILL

FIGURE 3-7

32° F ISOTHERM PLOT FOR E.P.R. RUN JV 0168

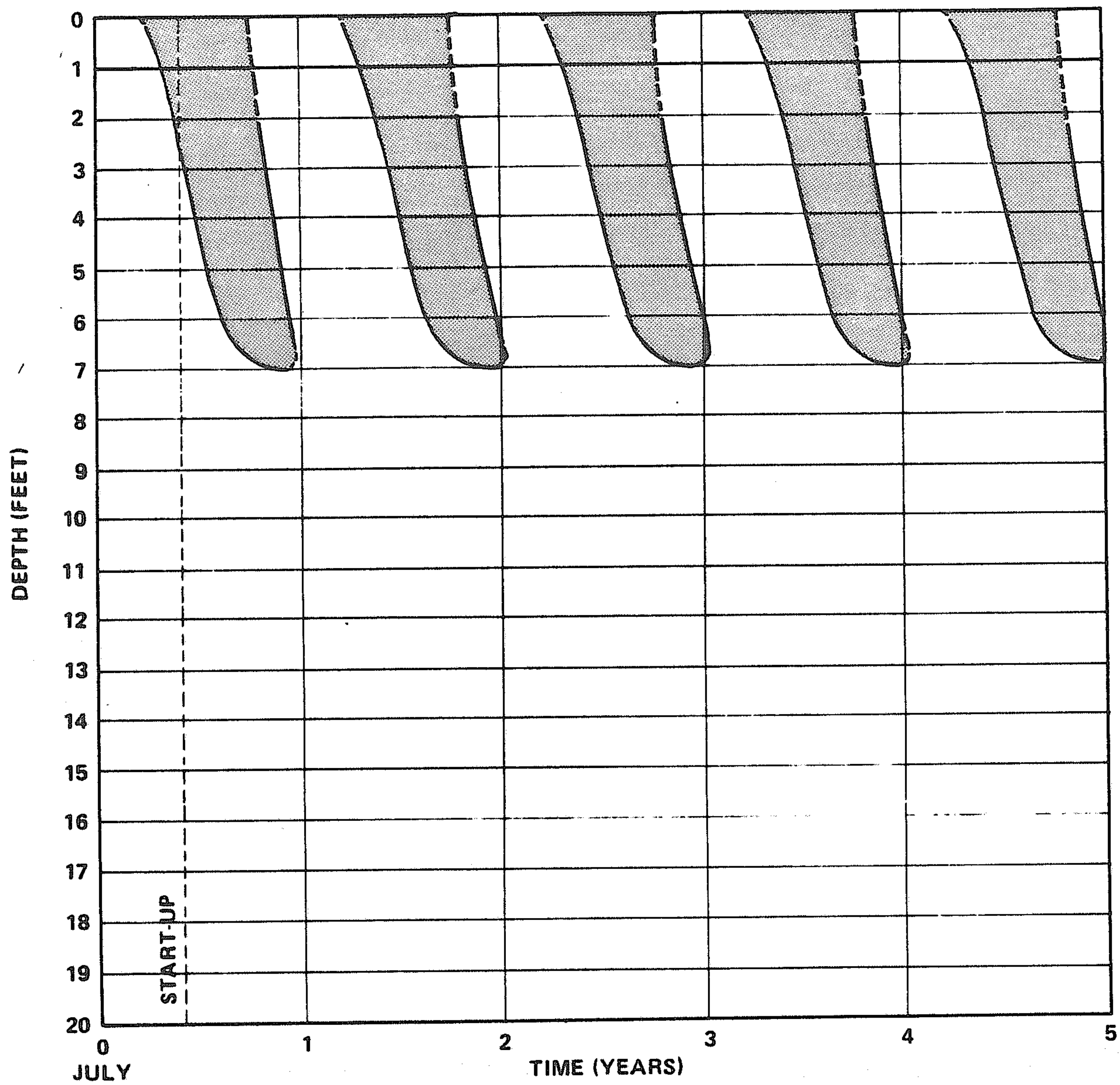


NONPERMAFROST ENVIRONMENT
12 INCHES POOLED SURFACE WATER
8 FOOT COVER DEPTH
5 INCH PIPE INSULATION
GAS OPERATING TEMP. = 15° F
INITIAL ANNUAL AVERAGE SOIL
TEMP. = 34.4° F AT 9.83' DEPTH
SATURATED GRAVEL NATIVE SOIL
SATURATED GRANULAR BACKFILL

BELOW 32° F

FIGURE 3 - 8

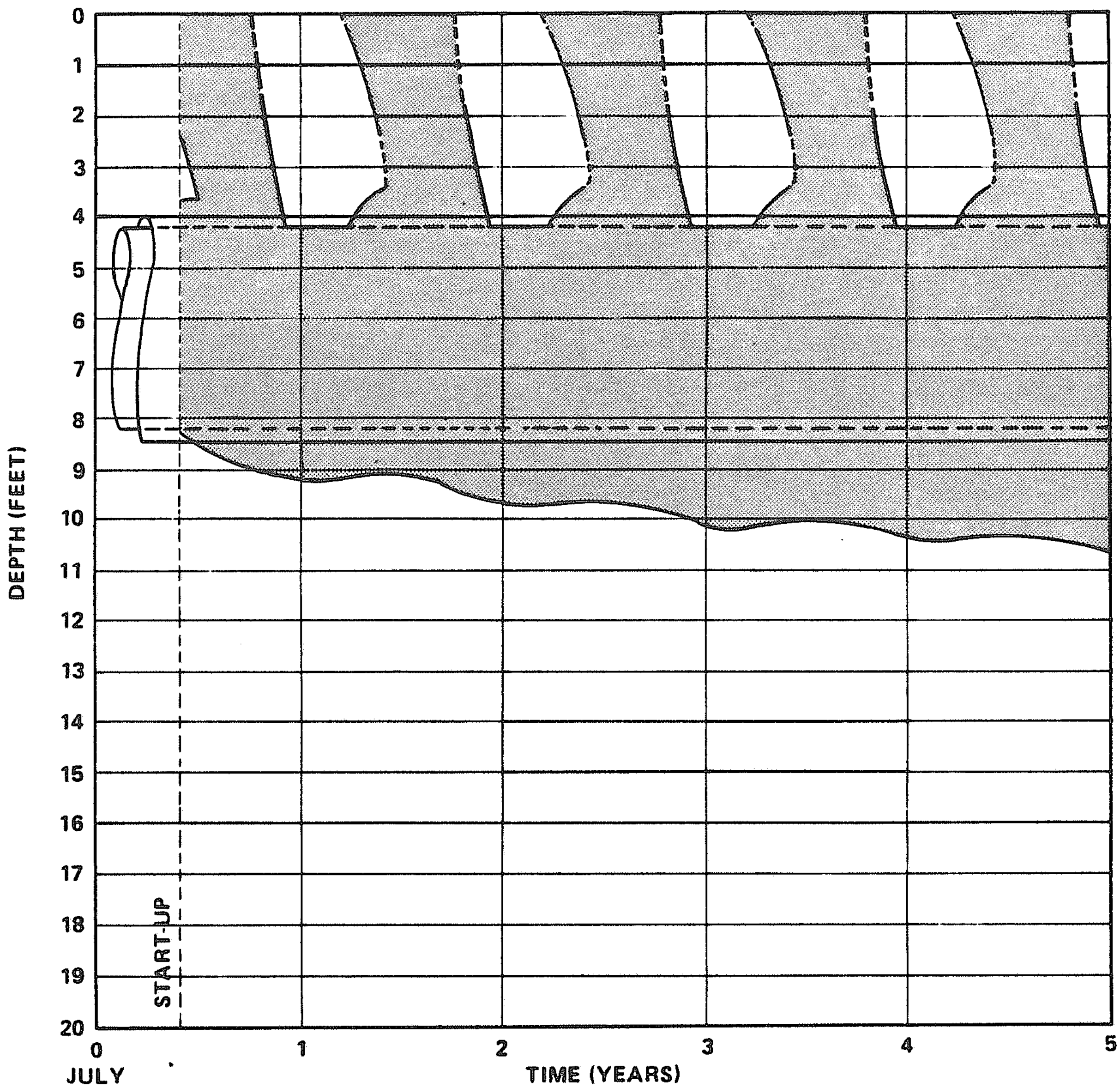
32° F ISOTHERM PLOT FOR E.P.R. RUN JV 0293



NONPERMAFROST ENVIRONMENT
NO SURFACE WATER
CONTROL RUN - NO PIPE
INITIAL ANNUAL AVERAGE SOIL
TEMP. = 34.5° F AT 9.17' DEPTH
SATURATED GRAVEL NATIVE SOIL

FIGURE 3 - 9

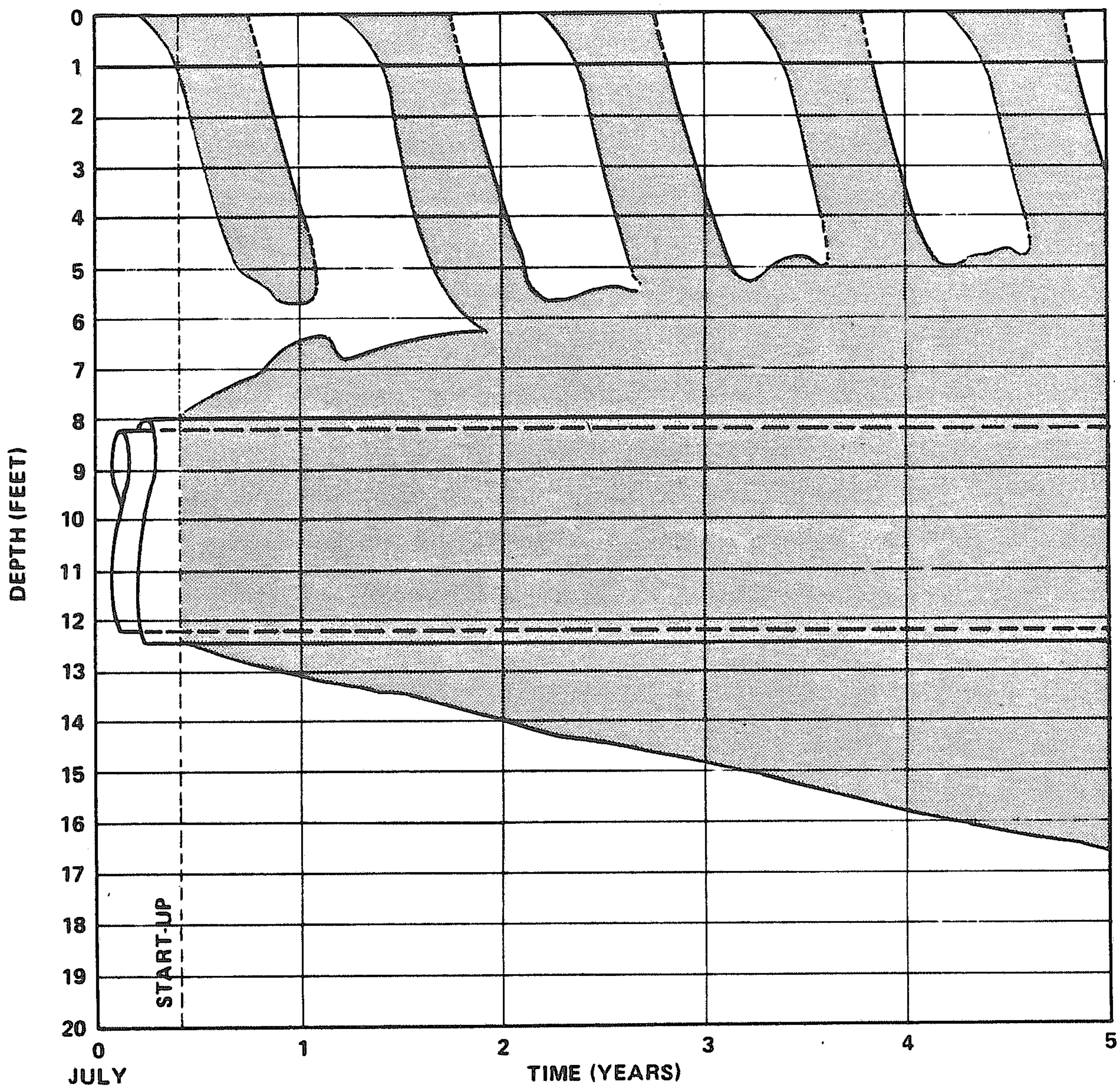
32° F ISOTHERM PLOT FOR E.P.R. RUN JV 0310



NONPERMAFROST ENVIRONMENT
NO SURFACE WATER
4 FOOT COVER DEPTH
3 INCH PIPE INSULATION
GAS OPERATING TEMP. = 15° F
INITIAL ANNUAL AVERAGE SOIL
TEMP. = 34.5° F AT 9.17' DEPTH
SATURATED GRAVEL NATIVE SOIL
SATURATED GRANULAR BACKFILL

FIGURE 3 - 10

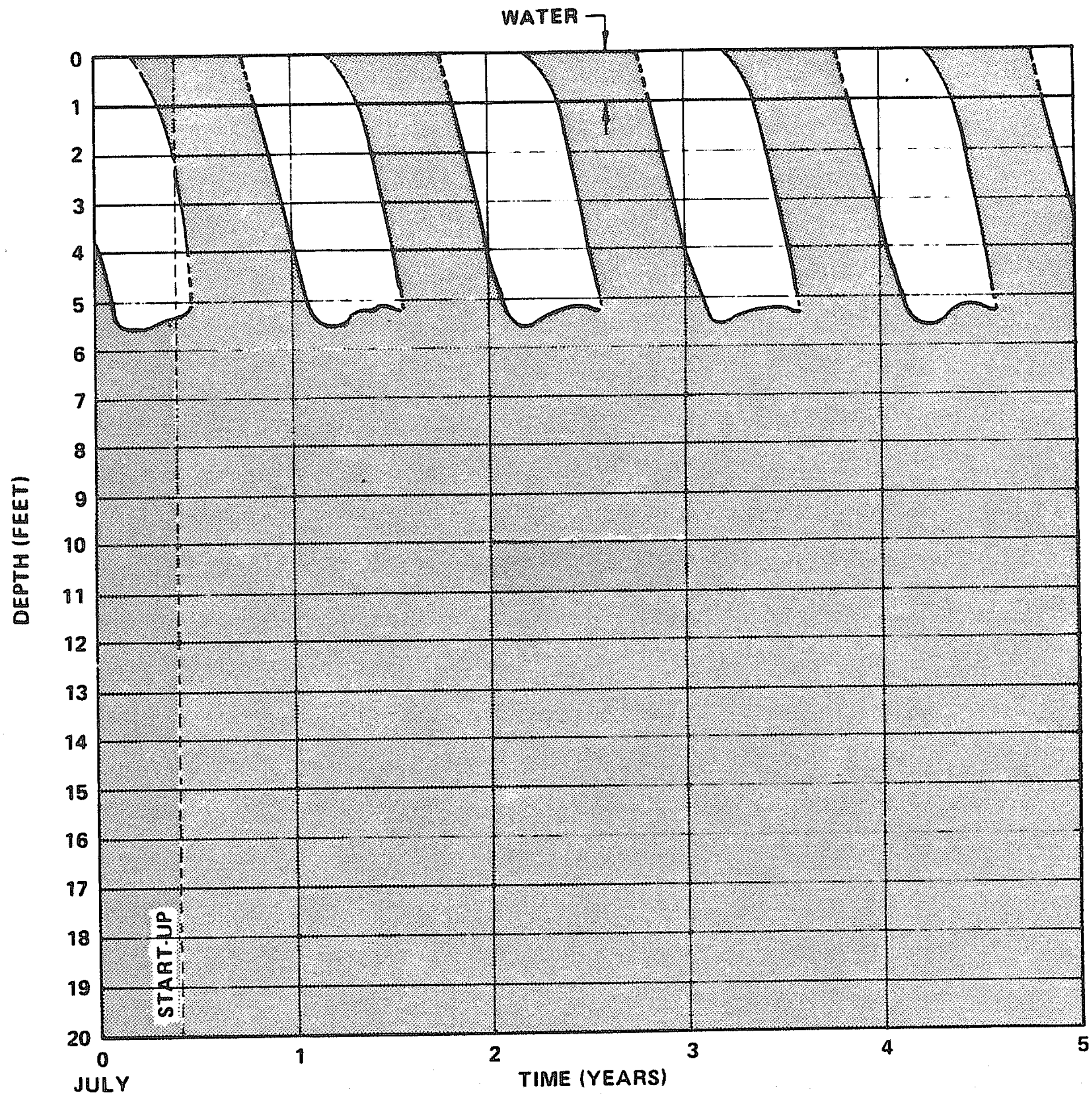
32° F ISOTHERM PLOT FOR E.P.R. RUN JV 0295



NONPERMAFROST ENVIRONMENT
NO SURFACE WATER
8 FOOT COVER DEPTH
3 INCH PIPE INSULATION
GAS OPERATING TEMP. = 15° F
INITIAL ANNUAL AVERAGE SOIL TEMP. = 34.5° F AT 9.17' DEPTH
SATURATED GRAVEL NATIVE SOIL
SATURATED GRANULAR BACKFILL

FIGURE 3-11

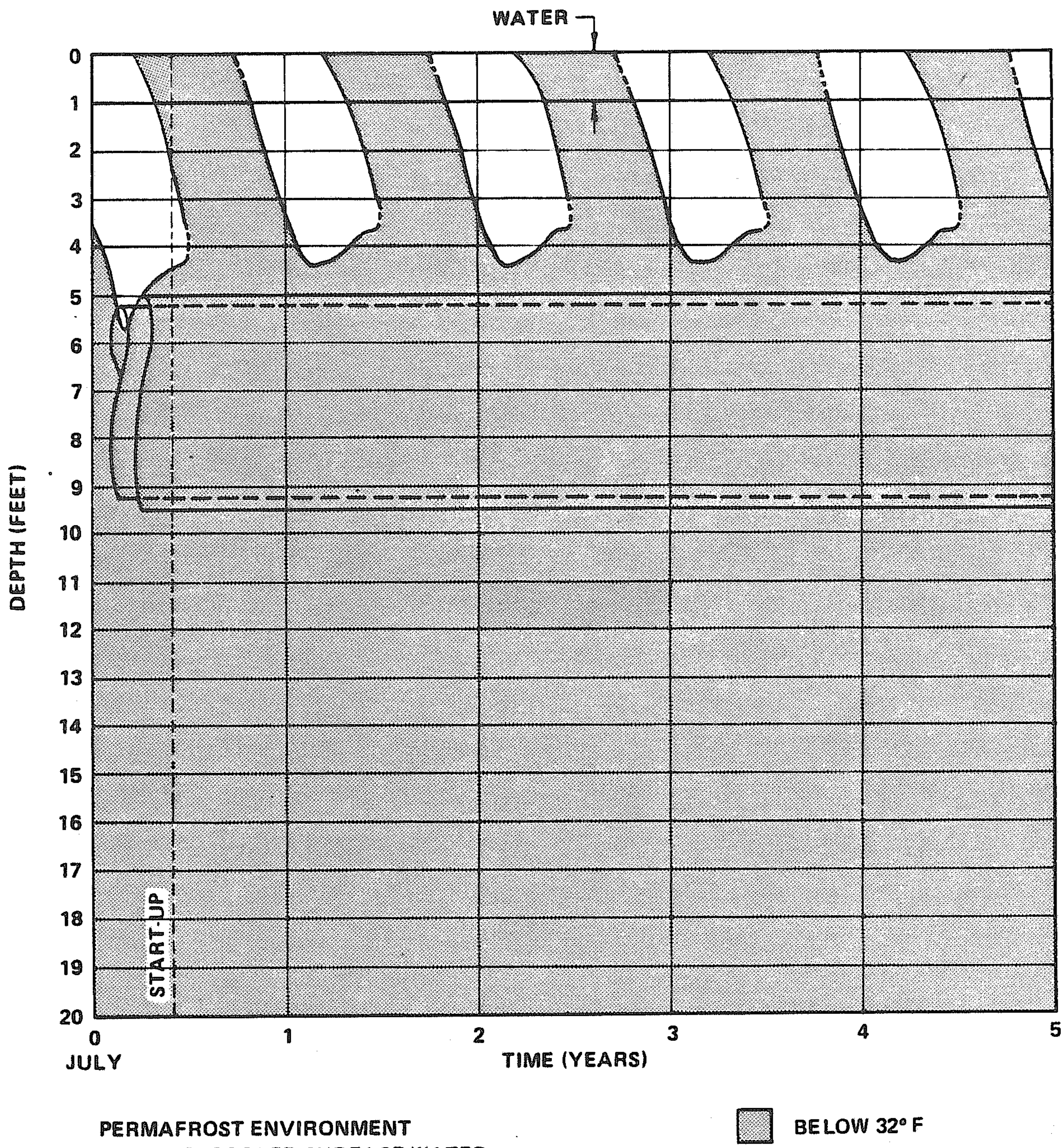
32° F ISOTHERM PLOT FOR E.P.R. RUN JV 0290



PERMAFROST ENVIRONMENT
12 INCHES POOLED SURFACE WATER
CONTROL RUN - NO PIPE
INITIAL ANNUAL AVERAGE SOIL
TEMP. = 31.0° F AT 9.17' DEPTH
SATURATED GRAVEL NATIVE SOIL

FIGURE 3 - 12

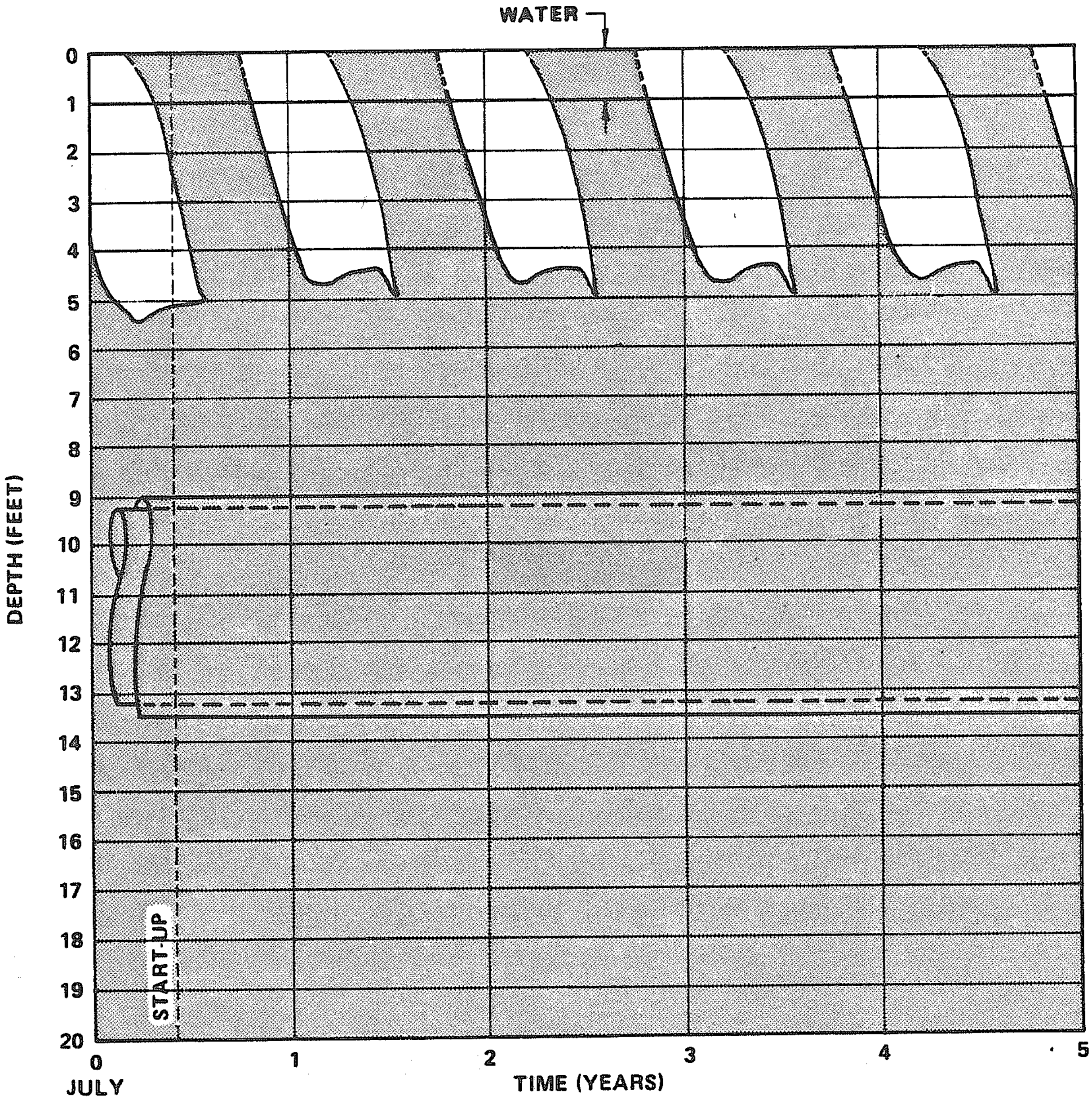
32° F ISOTHERM PLOT FOR E.P.R. RUN JV 0291



PERMAFROST ENVIRONMENT
12 INCHES POOLED SURFACE WATER
4 FOOT COVER DEPTH
3 INCH PIPE INSULATION
GAS OPERATING TEMP. = 15° F
INITIAL ANNUAL AVERAGE SOIL TEMP. = 31.0° F AT 9.17' DEPTH
SATURATED GRAVEL NATIVE SOIL
SATURATED GRANULAR BACKFILL

FIGURE 3-13

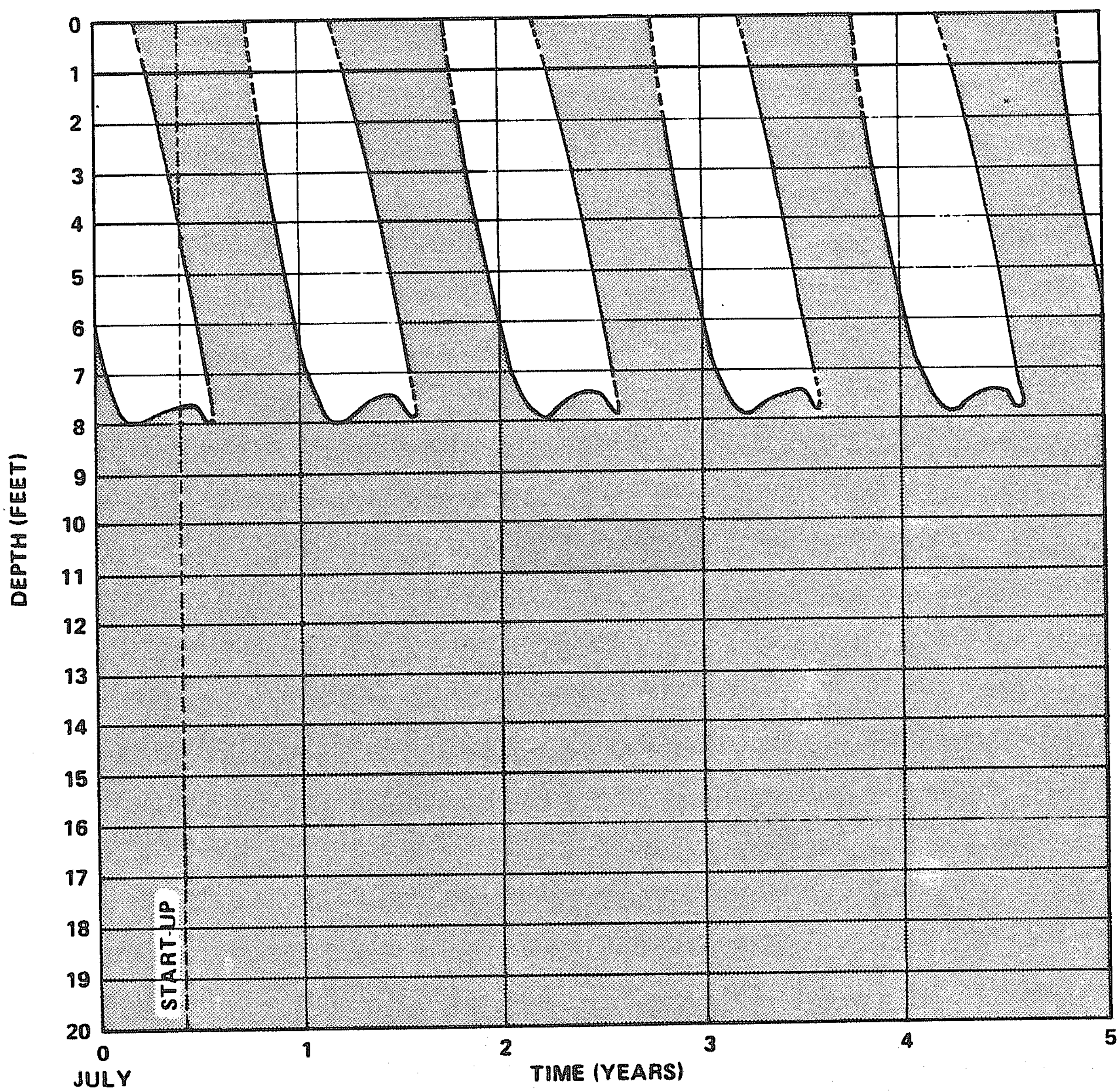
32° F ISOTHERM PLOT FOR E.P.R. RUN JV 0292



PERMAFROST ENVIRONMENT
12 INCHES POOLED SURFACE WATER
8 FOOT COVER DEPTH
3 INCH PIPE INSULATION
GAS OPERATING TEMP. = 15° F
INITIAL ANNUAL AVERAGE SOIL TEMP. = 31.0°F AT 9.17' DEPTH
SATURATED GRAVEL NATIVE SOIL
SATURATED GRANULAR BACKFILL

FIGURE 3 - 14

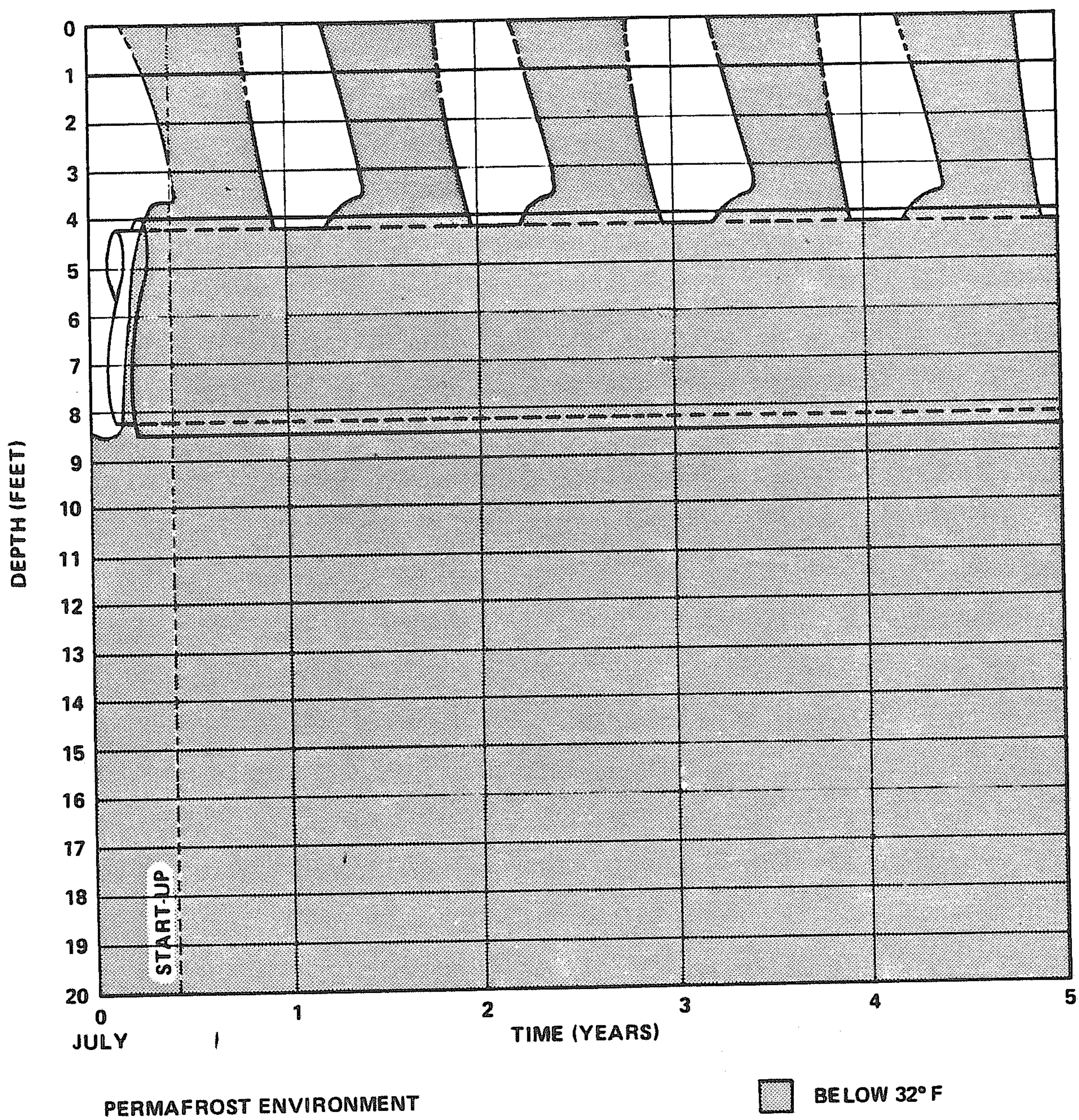
32° F ISOTHERM PLOT FOR E.P.R. RUN JV 0289



PERMAFROST ENVIRONMENT
NO SURFACE WATER
CONTROL RUN - NO PIPE
INITIAL ANNUAL AVERAGE SOIL
TEMP. = 30.4° F AT 9.17' DEPTH
SATURATED GRAVEL NATIVE SOIL

FIGURE 3 - 15

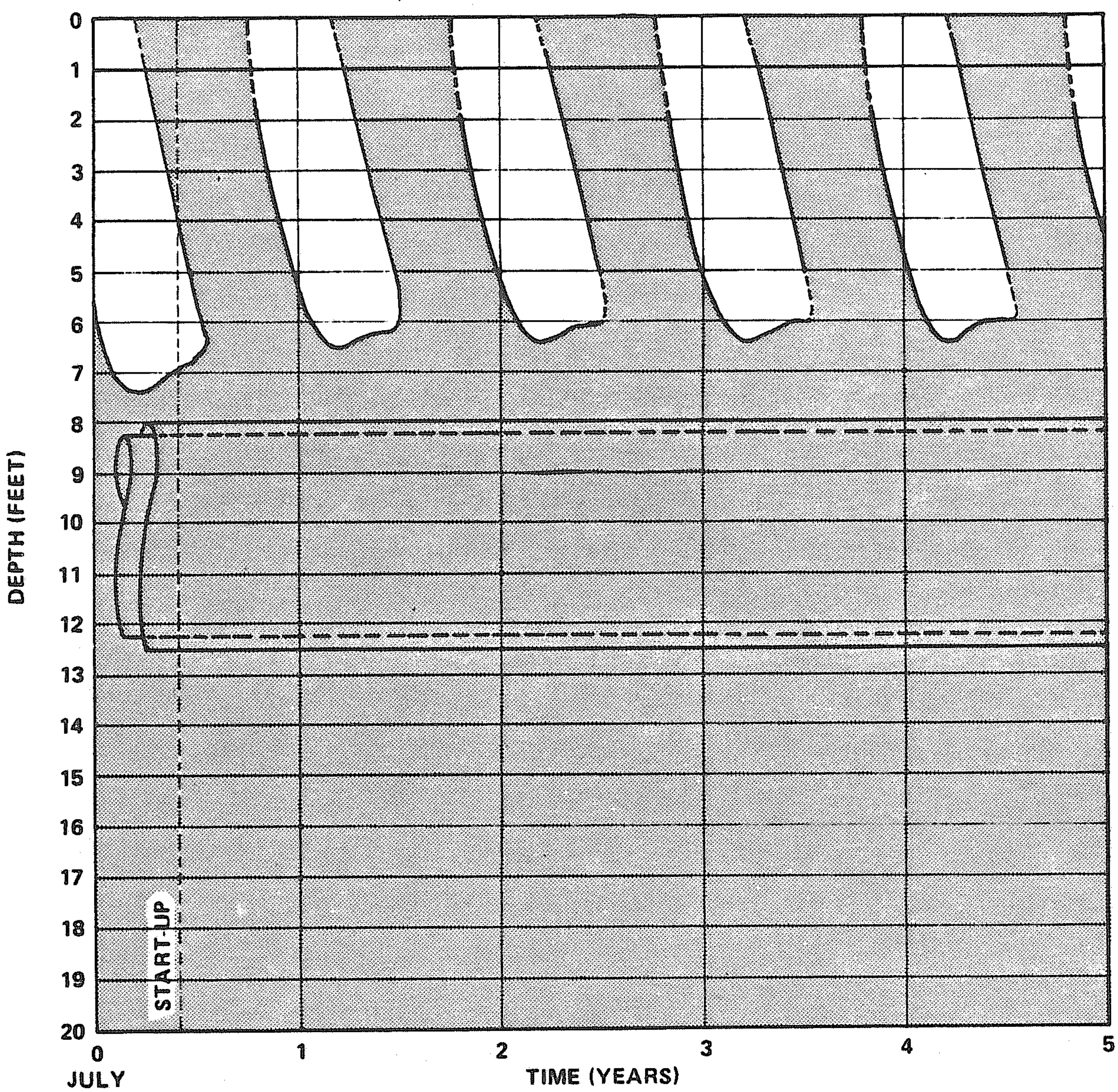
32° F ISOTHERM PLOT FOR E.P.R. RUN JV 0307



PERMAFROST ENVIRONMENT
NO SURFACE WATER
4 FOOT COVER DEPTH
3 INCH PIPE INSULATION
GAS OPERATING TEMP. = 15° F
INITIAL ANNUAL AVERAGE SOIL
TEMP. = 30.4° F AT 9.17' DEPTH
SATURATED GRAVEL NATIVE SOIL
SATURATED GRANULAR BACKFILL

FIGURE 3 - 16

32° F ISOTHERM PLOT FOR E.P.R. RUN JV 0308



PERMAFROST ENVIRONMENT
NO SURFACE WATER
8 FOOT COVER DEPTH
3 INCH PIPE INSULATION
GAS OPERATING TEMP. = 15° F
INITIAL ANNUAL AVERAGE SOIL
TEMP. = 30.4° F AT 9.17' DEPTH
SATURATED GRAVEL NATIVE SOIL
SATURATED GRANULAR BACKFILL

FIGURE 3 - 17

NWA

PORFLOW–F GRID USED IN SIMULATIONS

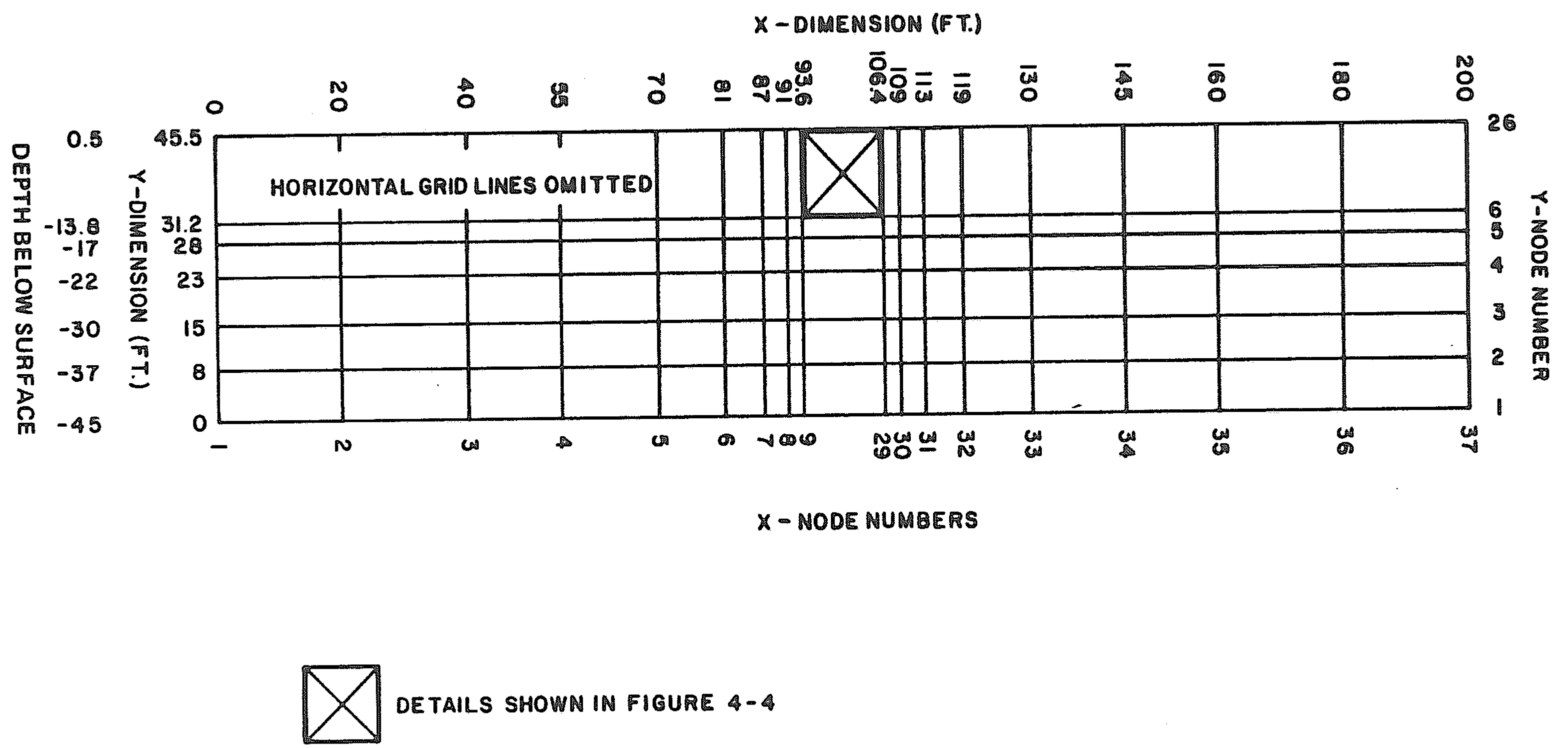
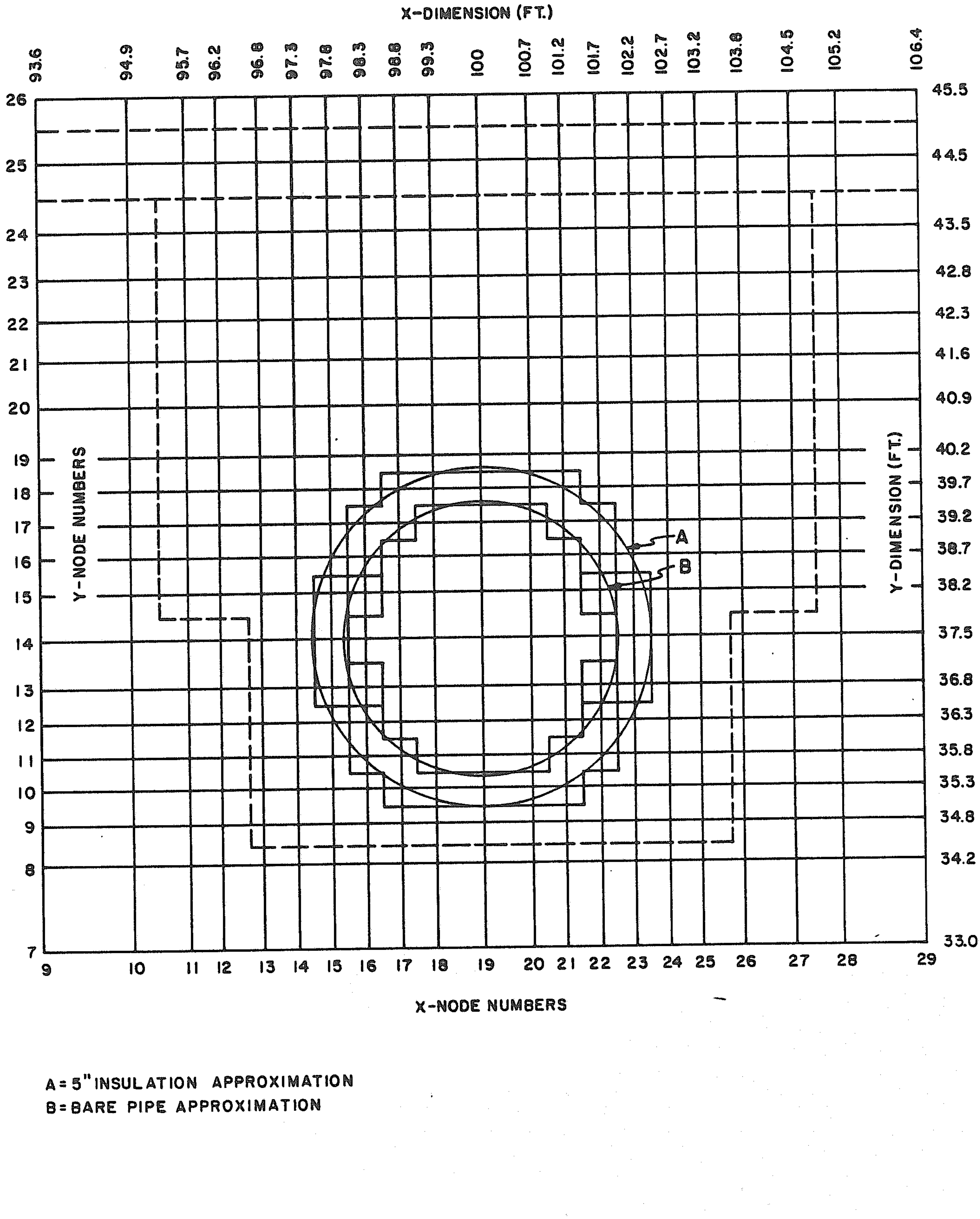


FIGURE 4-1

CHILLED PIPE EFFECTS ON STREAMS

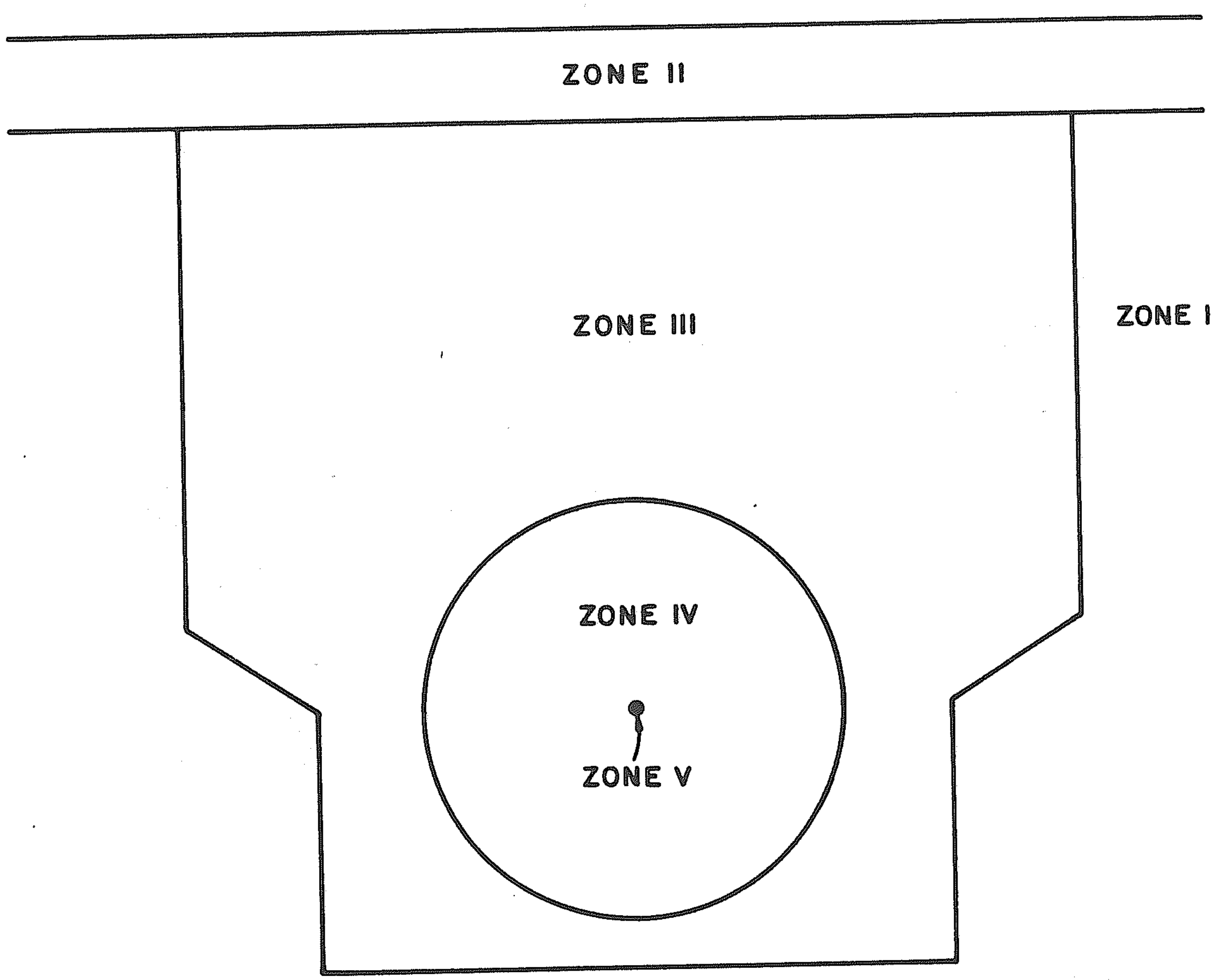
PORFLOW–F GRID AROUND THE PIPELINE



A = 5" INSULATION APPROXIMATION
B = BARE PIPE APPROXIMATION

FIGURE 4 - 2

ZONES USED TO DEFINE GEOTHERMAL AND HYDROGEOLOGICAL PROPERTIES



ZONE I - NATIVE SOIL
ZONE II - STREAM
ZONE III - DITCH BACKFILL
ZONE IV - PIPE & INSULATION
ZONE V - CENTER OF PIPE

FIGURE 4 - 3

SURFACE WATER DEPTH VARIATION
TEMPERATURE VARIATION AT 0.5 FT. BELOW THE WATER BODY

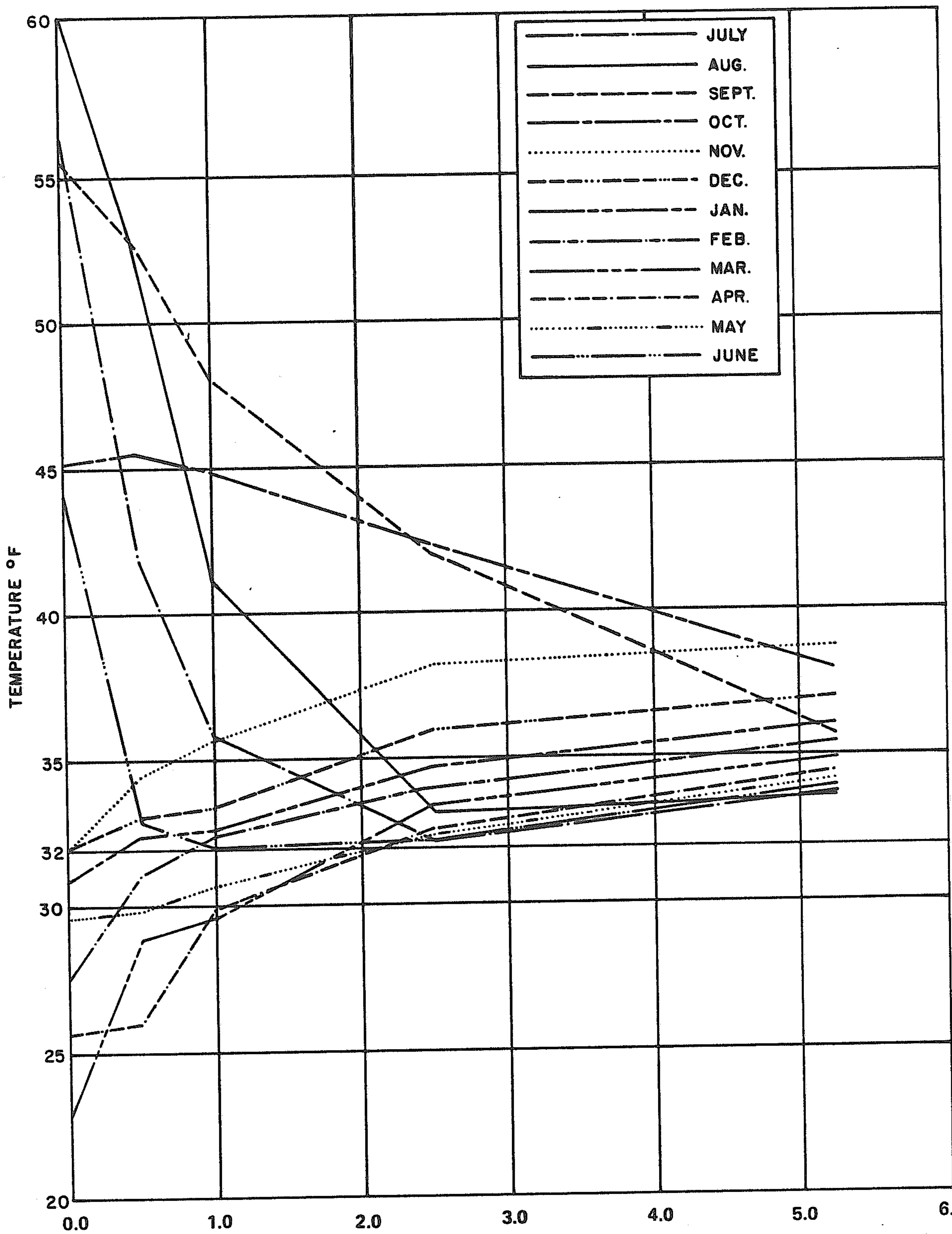


FIGURE 4 - 4

SURFACE WATER DEPTH VARIATION
TEMPERATURE VARIATION AT 2.4 FT. BELOW THE WATER BODY

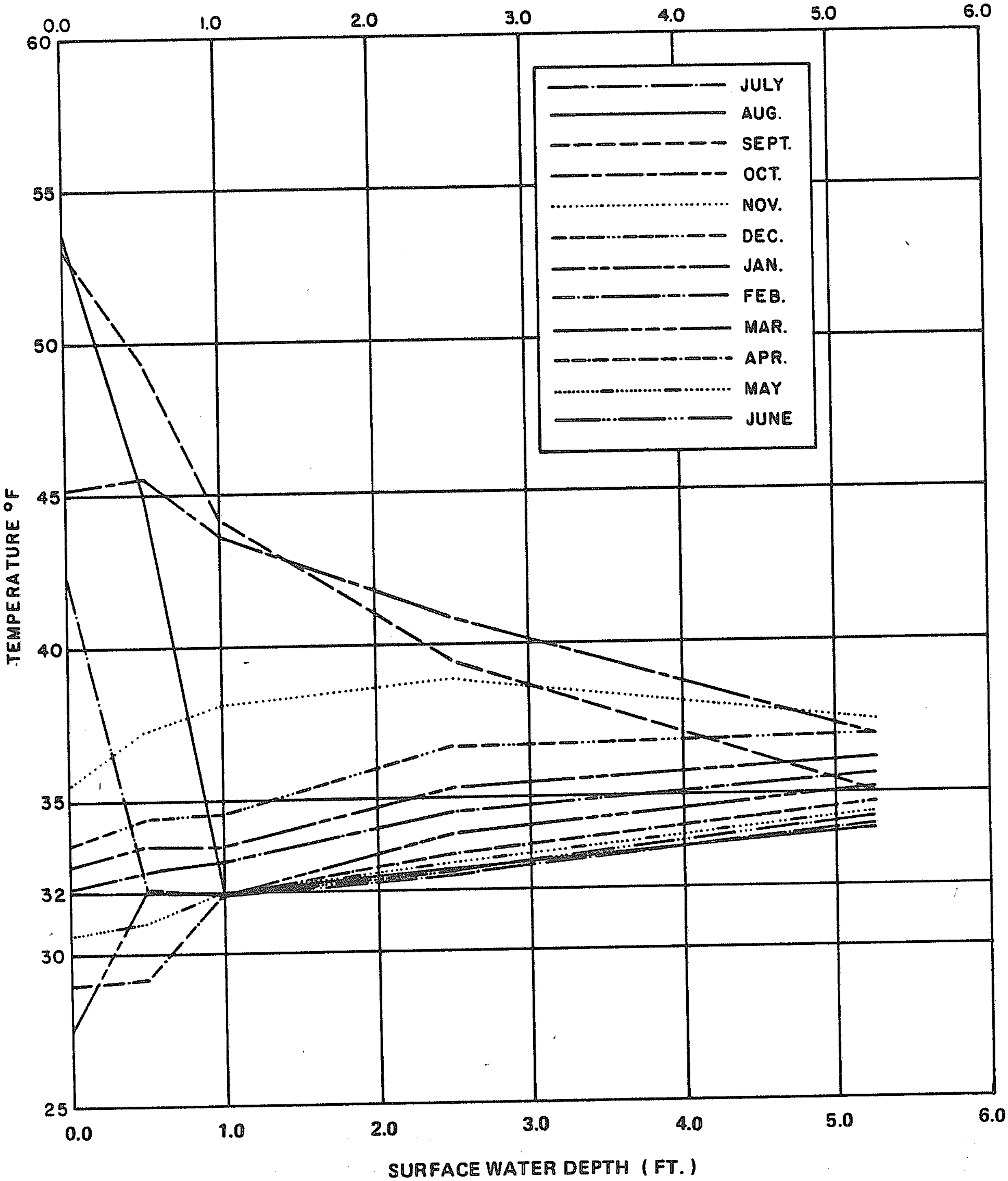
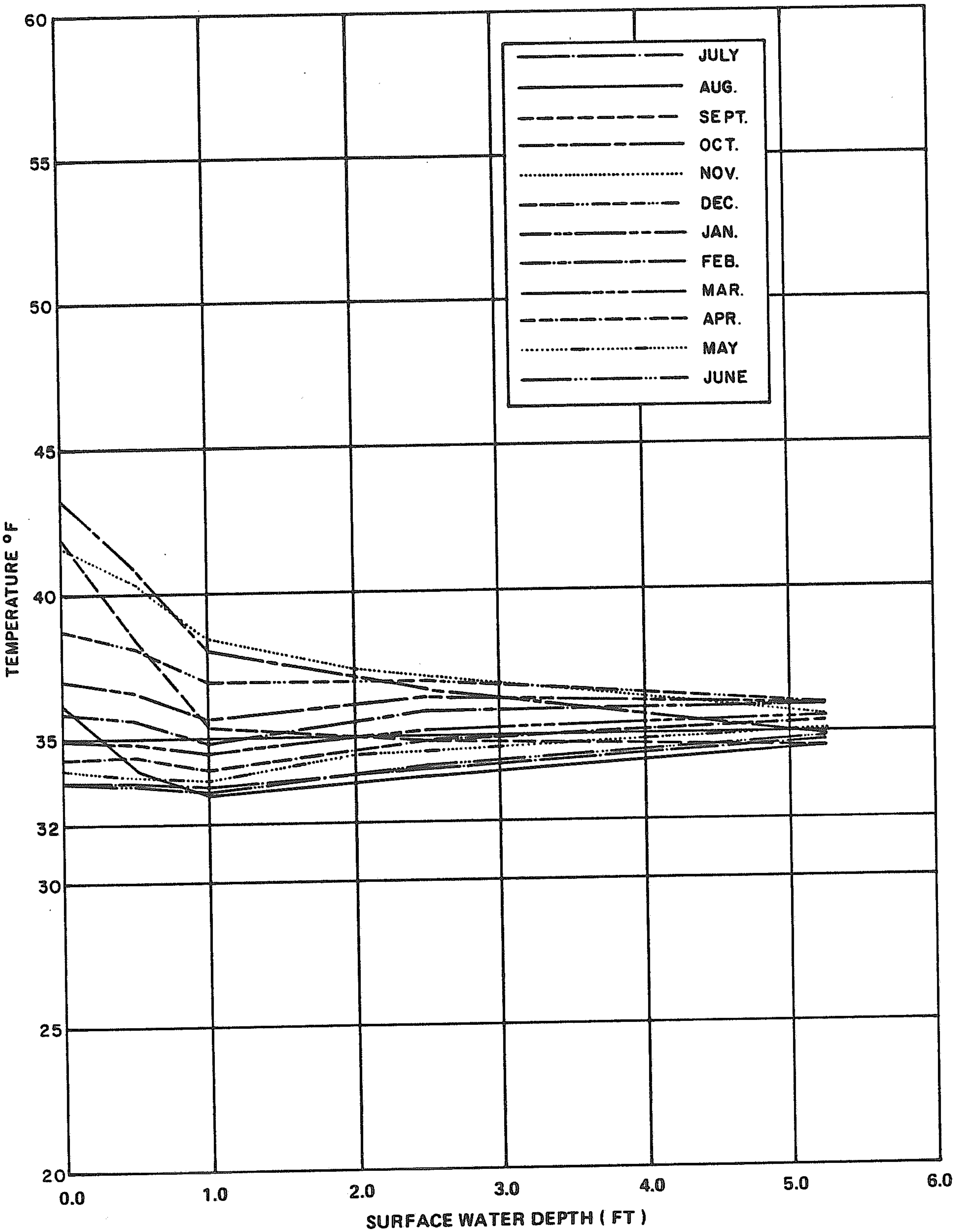


FIGURE 4 - 5

SURFACE WATER DEPTH VARIATION
TEMPERATURE VARIATION AT 9.8 FT. BELOW THE WATER BODY



NOTE : MAXIMUM TEMPERATURE VARIATION DECREASES WITH INCREASING STREAM DEPTH.

FIGURE 4 - 6

SURFACE WATER DEPTH VARIATION
ANNUAL TEMPERATURE VARIATION

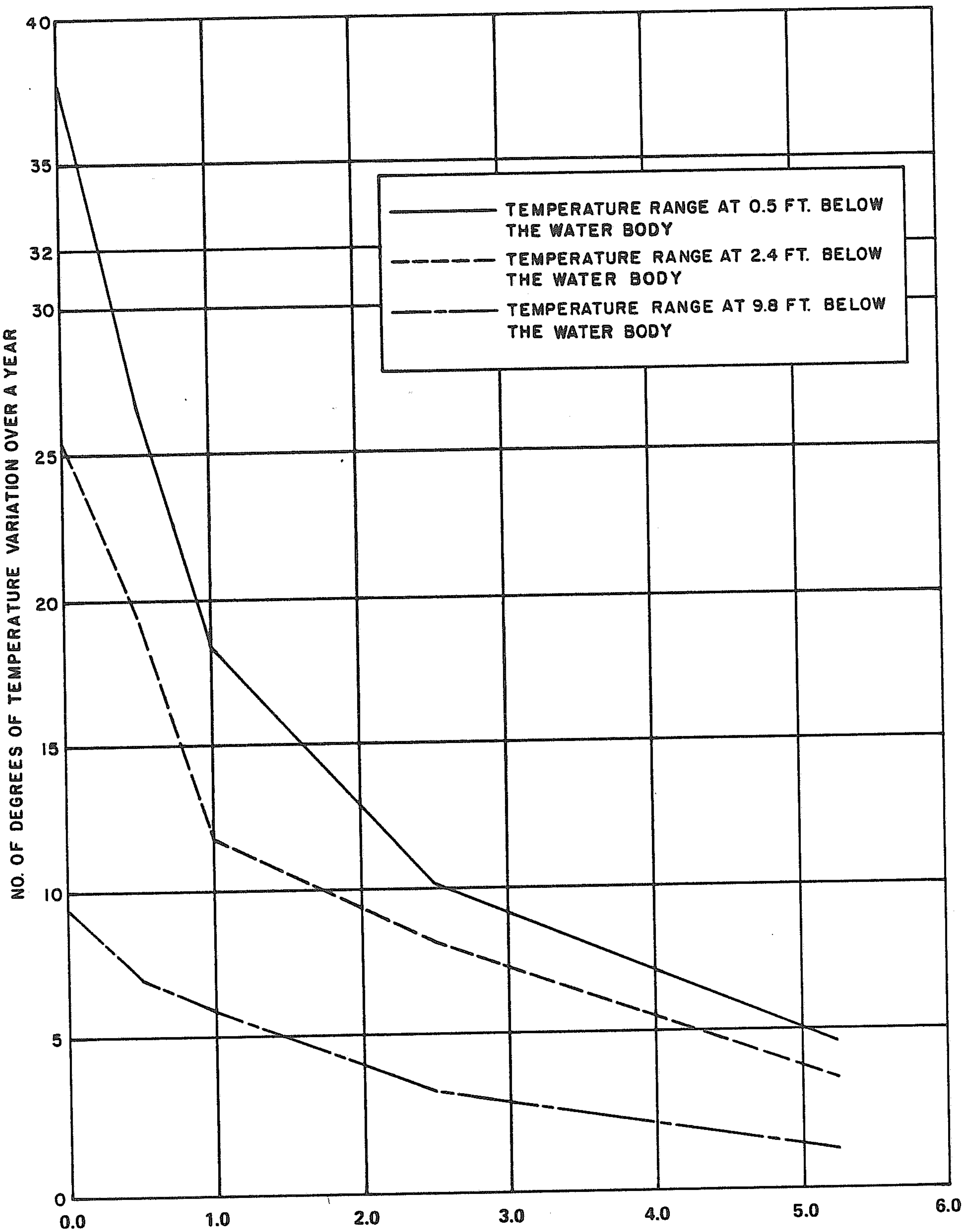


FIGURE 4 - 7

SURFACE WATER DEPTH VARIATION
VARIATION IN MAXIMUM FREEZE DEPTHS

POR-FLOW

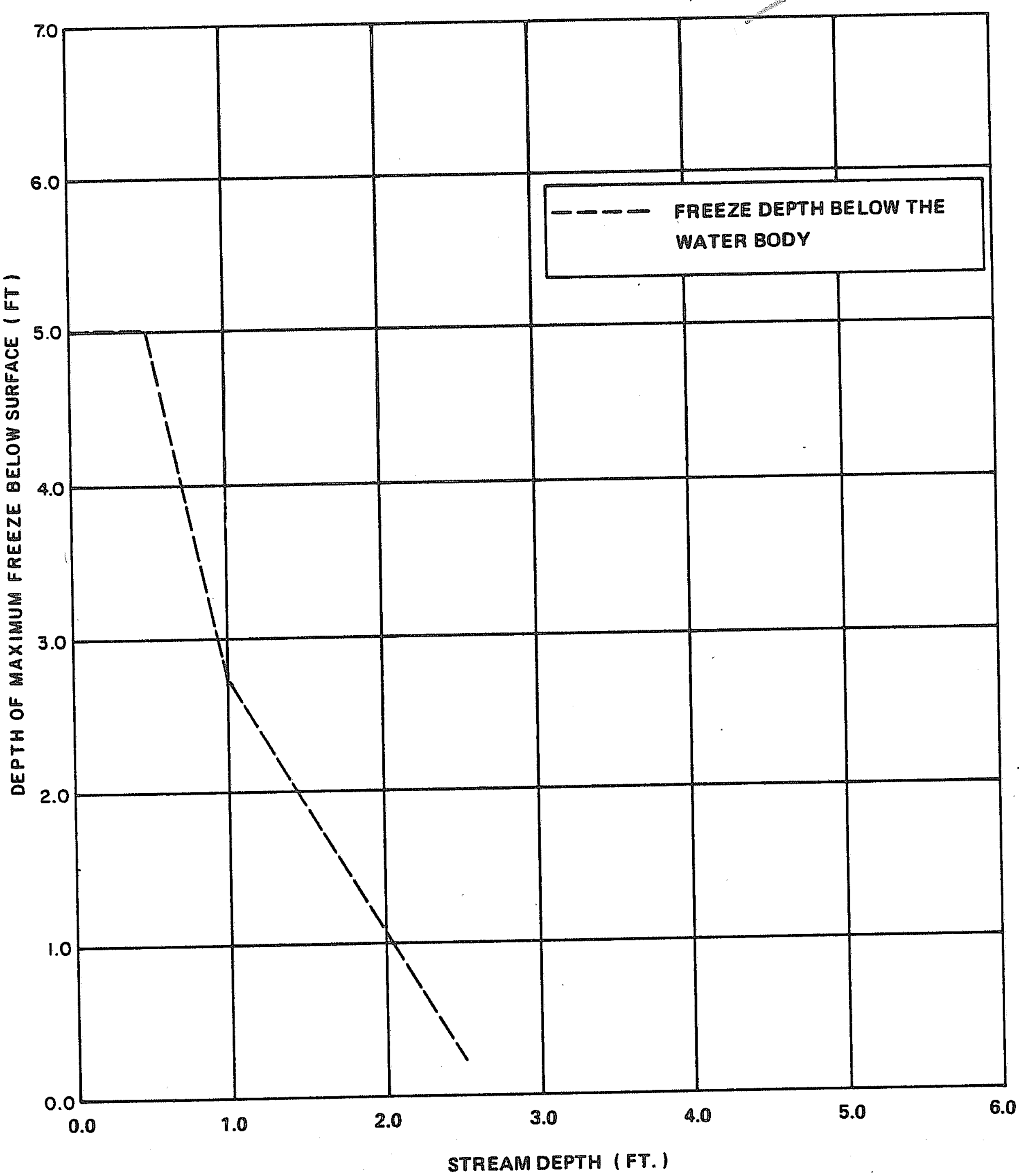
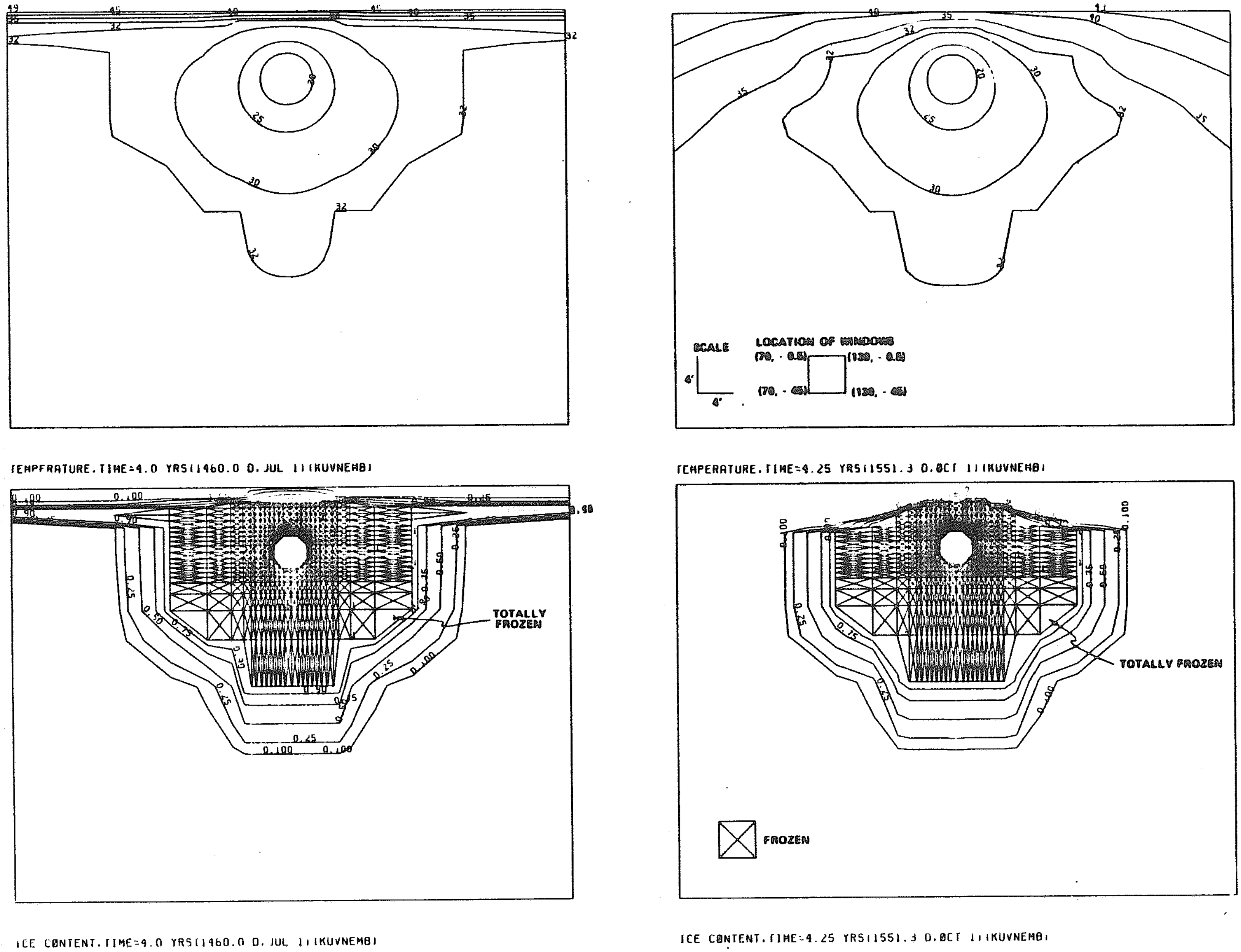


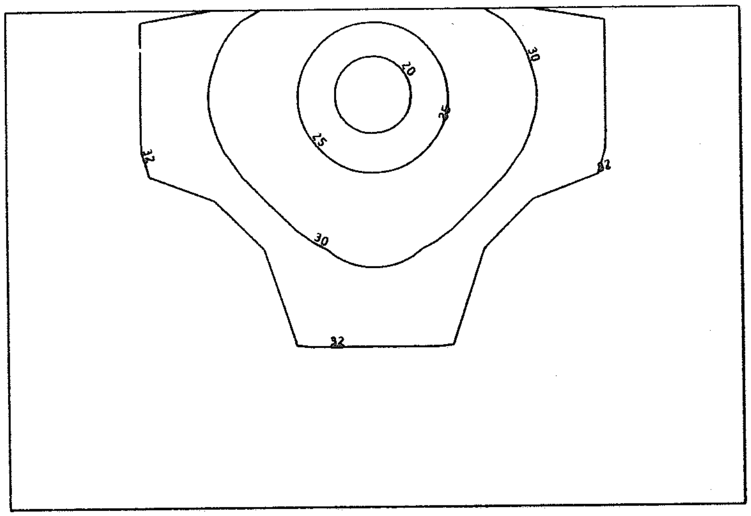
FIGURE 4 - 8

FIGURE 4 - 9

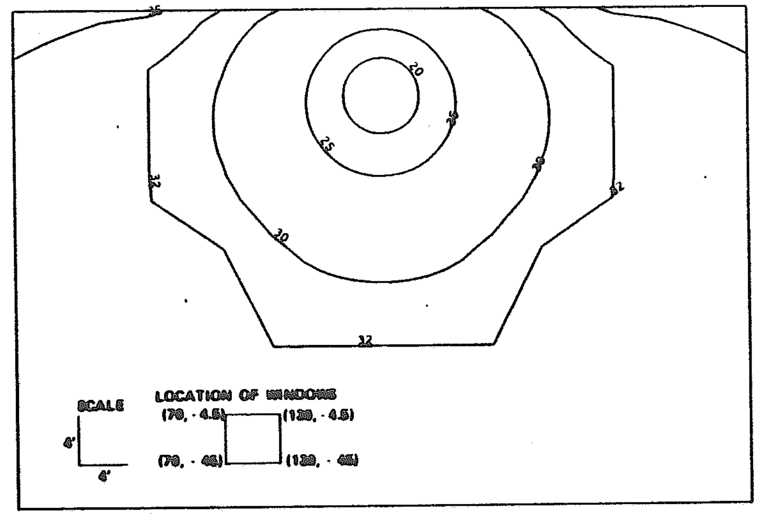
TEMPERATURE AND ICE CONTENT PLOTS FOR BARE PIPE OPERATION. SURFACE WATER DEPTH IS 1 FOOT, GAS TEMPERATURE IS 15° F (CONTOUR INTERVALS ARE VARIABLE)



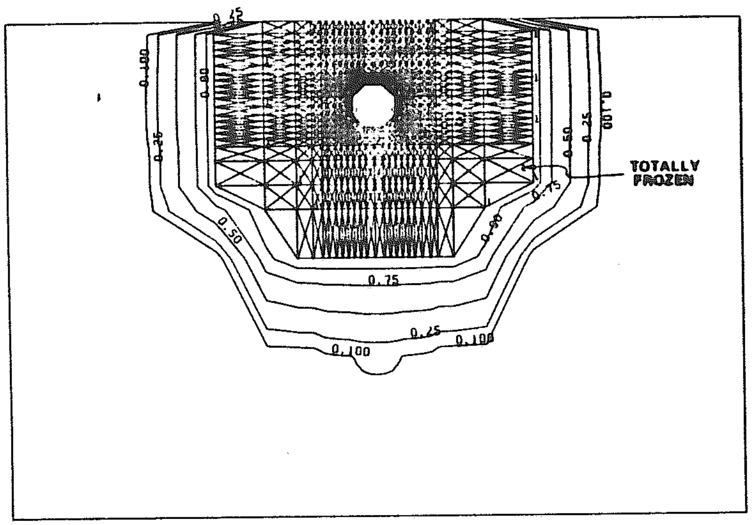
TEMPERATURE AND ICE CONTENT PLOTS FOR BARE PIPE OPERATION. SURFACE WATER DEPTH IS 5.25 FEET, GAS TEMPERATURE IS 15° F (CONTOUR INTERVALS ARE VARIABLE)



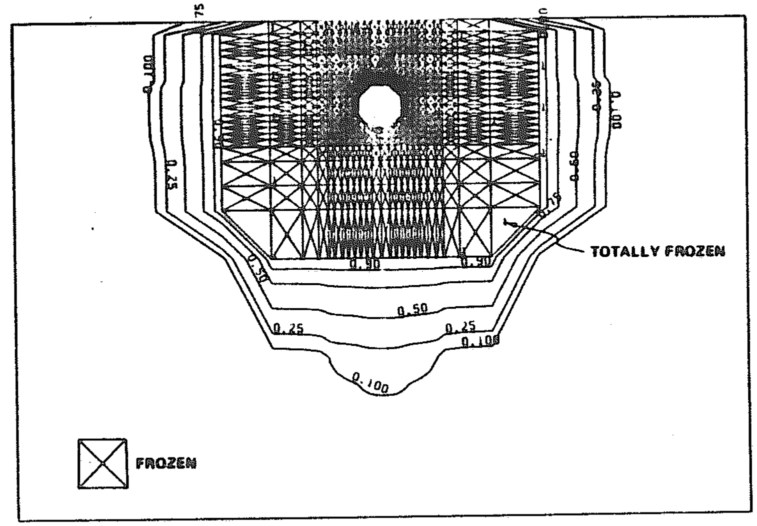
TEMPERATURE.TIME=4.0 YRS(1460.0 D.JUL 1)(KUVFDP7)



TEMPERATURE.TIME=4.25 YRS(1551.3 D.OCT 1)(KUVFDP7)



ICE CONTENT.TIME=4.0 YRS(1460.0 D.JUL 1)(KUVFDP7)

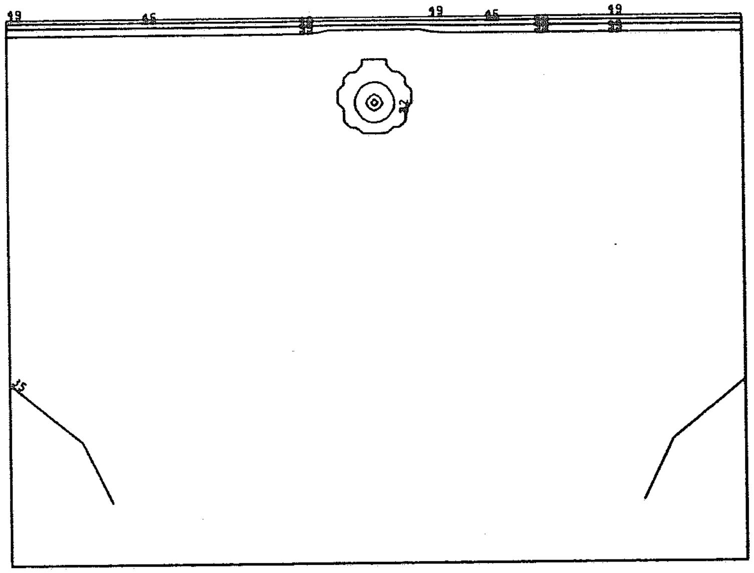


ICE CONTENT.TIME=4.25 YRS(1551.3 D.OCT 1)(KUVFDP7)

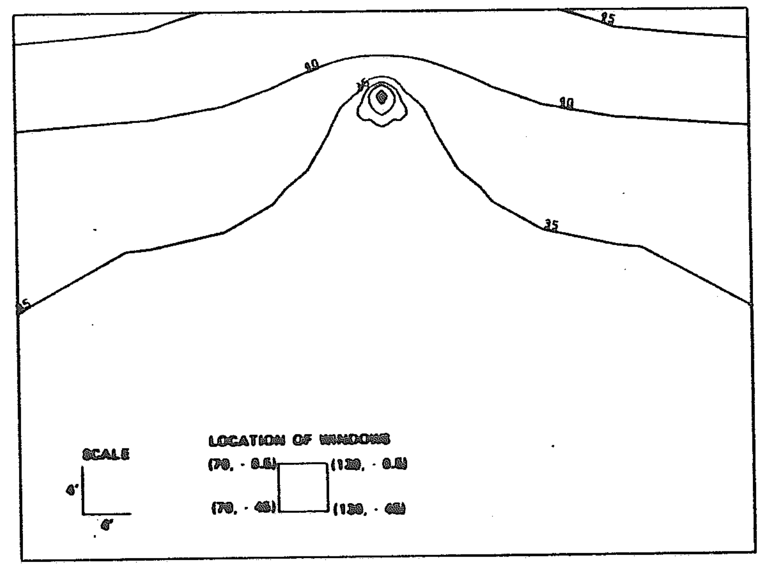
FIGURE 4 - 10

FIGURE 4 - 11

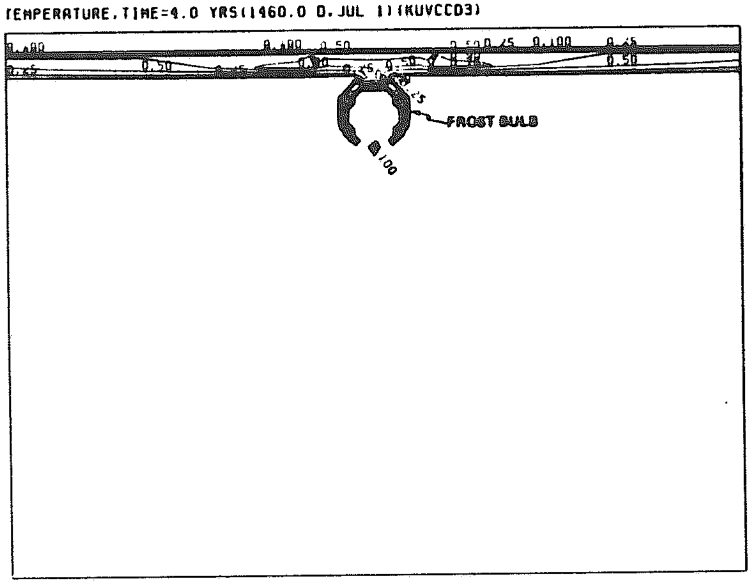
TEMPERATURE AND ICE CONTENT PLOTS FOR BARE PIPE OPERATION. SURFACE WATER DEPTH IS 1 FOOT, GAS TEMPERATURE IS 15° F. 3" CIRCULAR INSULATION (CONTOUR INTERVALS ARE VARIABLE)



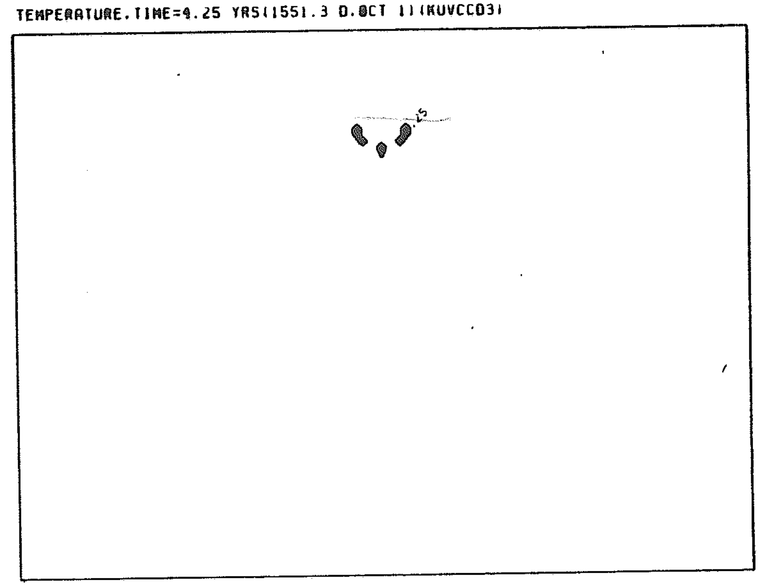
TEMPERATURE, TIME=4.0 YRS(1460.0 D. JUL 1)(KUVCCD3)



TEMPERATURE, TIME=4.25 YRS(1551.3 D. OCT 1)(KUVCCD3)



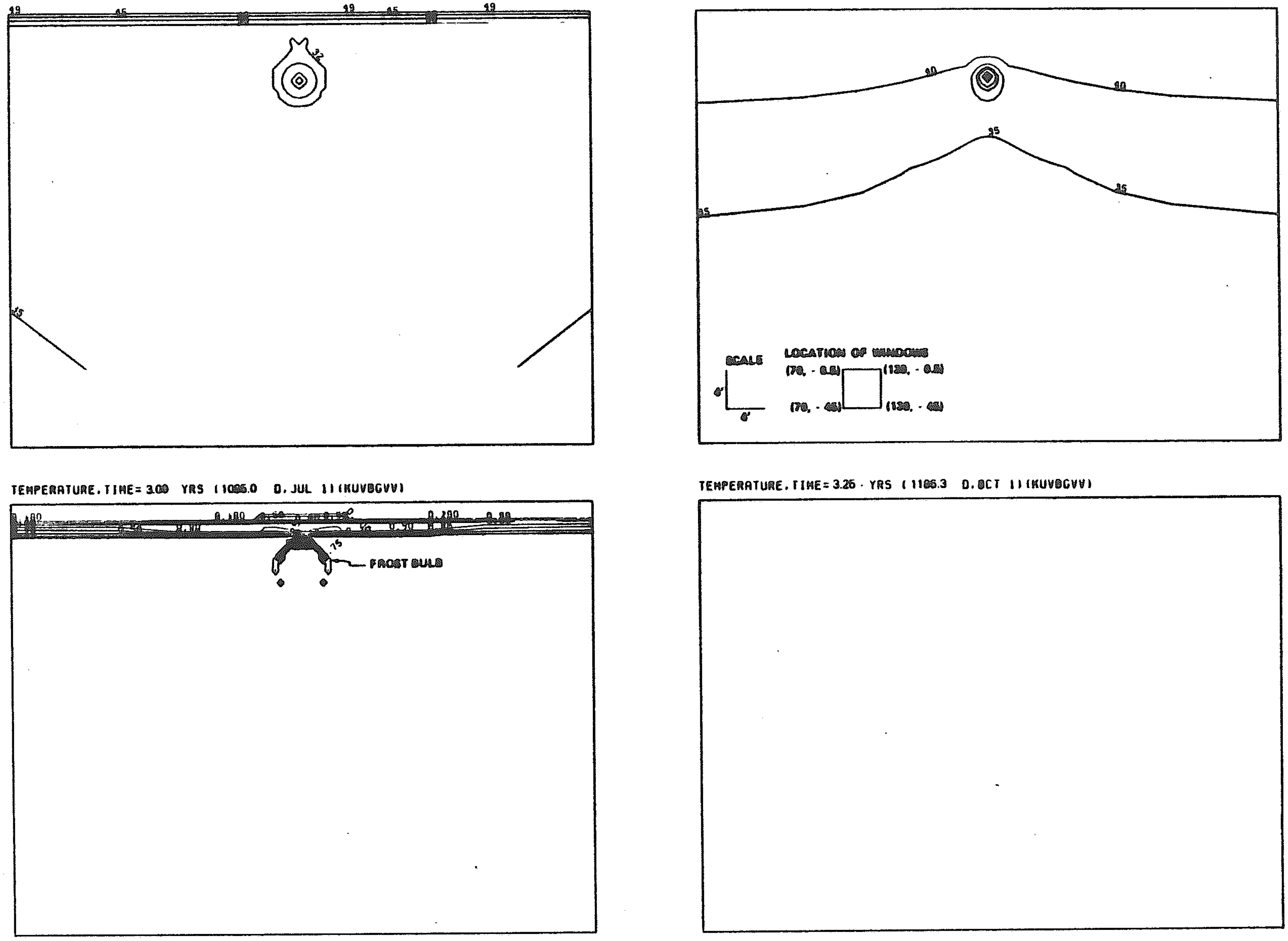
ICE CONTENT, TIME=4.0 YRS(1460.0 D. JUL 1)(KUVCCD3)



ICE CONTENT, TIME=4.25 YRS(1551.3 D. OCT 1)(KUVCCD3)

FIGURE 4 - 12

TEMPERATURE AND ICE CONTENT PLOTS FOR BARE PIPE OPERATION. SURFACE WATER DEPTH IS 1 FOOT, GAS TEMPERATURE IS 15° F. 5" CIRCULAR INSULATION (CONTOUR INTERVALS ARE VARIABLE)



TEMPERATURE. TIME= 3.00 YRS (1095.0 D. JUL 1) (KUVBGVV)

TEMPERATURE. TIME= 3.25 YRS (1186.3 D. OCT 1) (KUVBGVV)

ICE CONTENT. TIME= 3.00 YRS (1095.0 D. JUL 1) (KUVBGVV)

ICE CONTENT. TIME= 3.25 YRS (1186.3 D. OCT 1) (KUVBGVV)

STREAM TEMPERATURE VARIATION
STREAM TEMPERATURE ASSIGNED TO STREAM FLOW

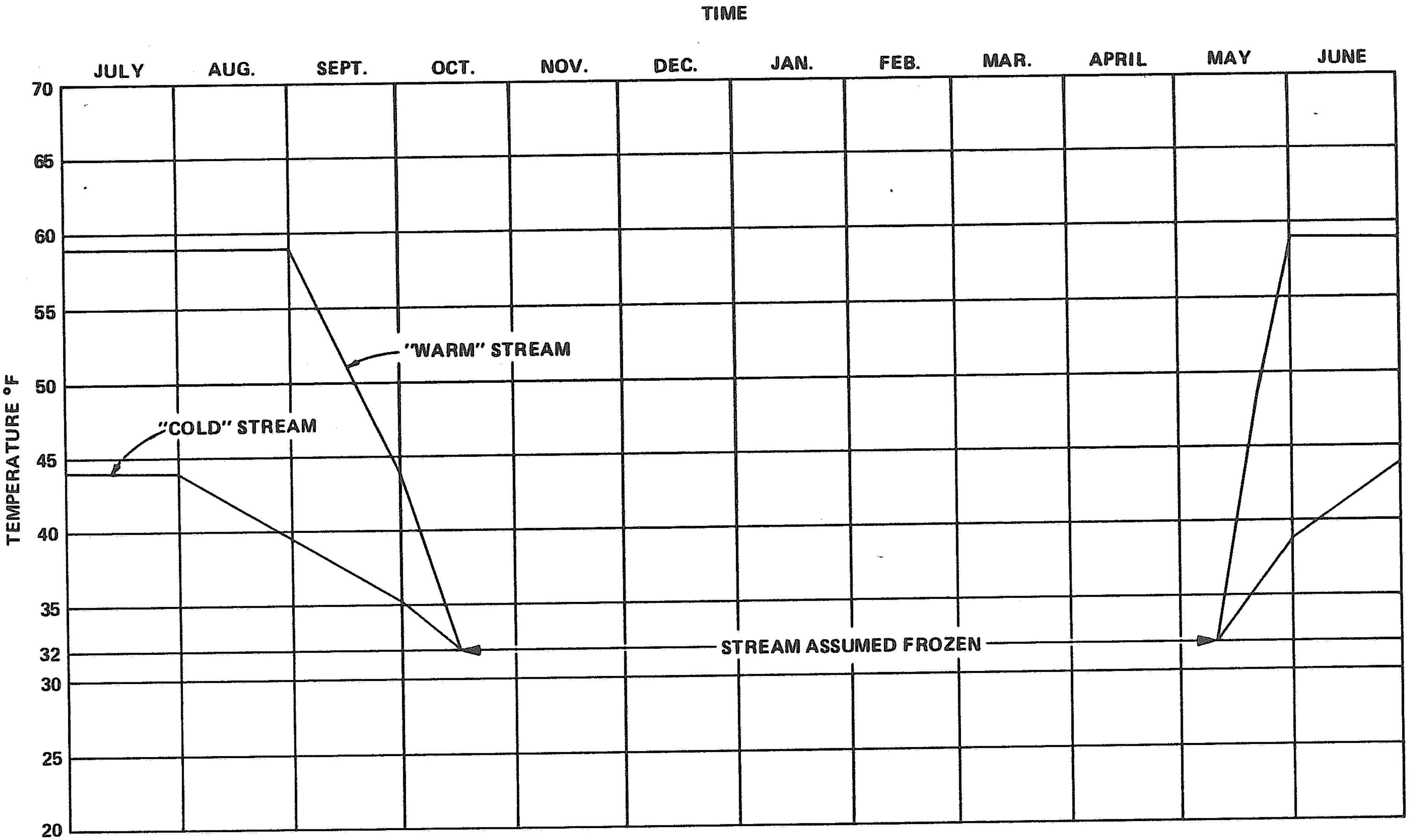
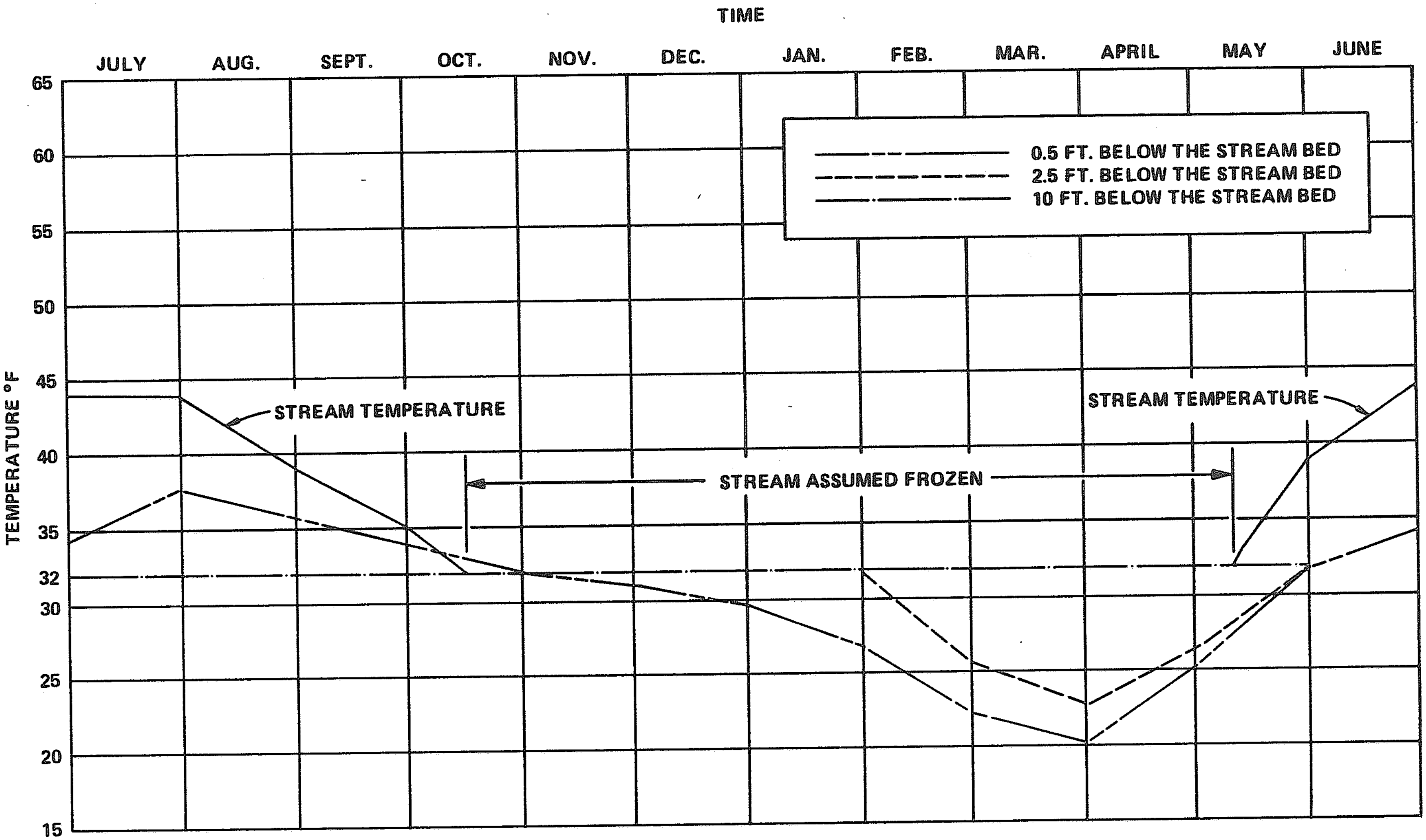


FIGURE 4 - 13

FIGURE 4 - 14

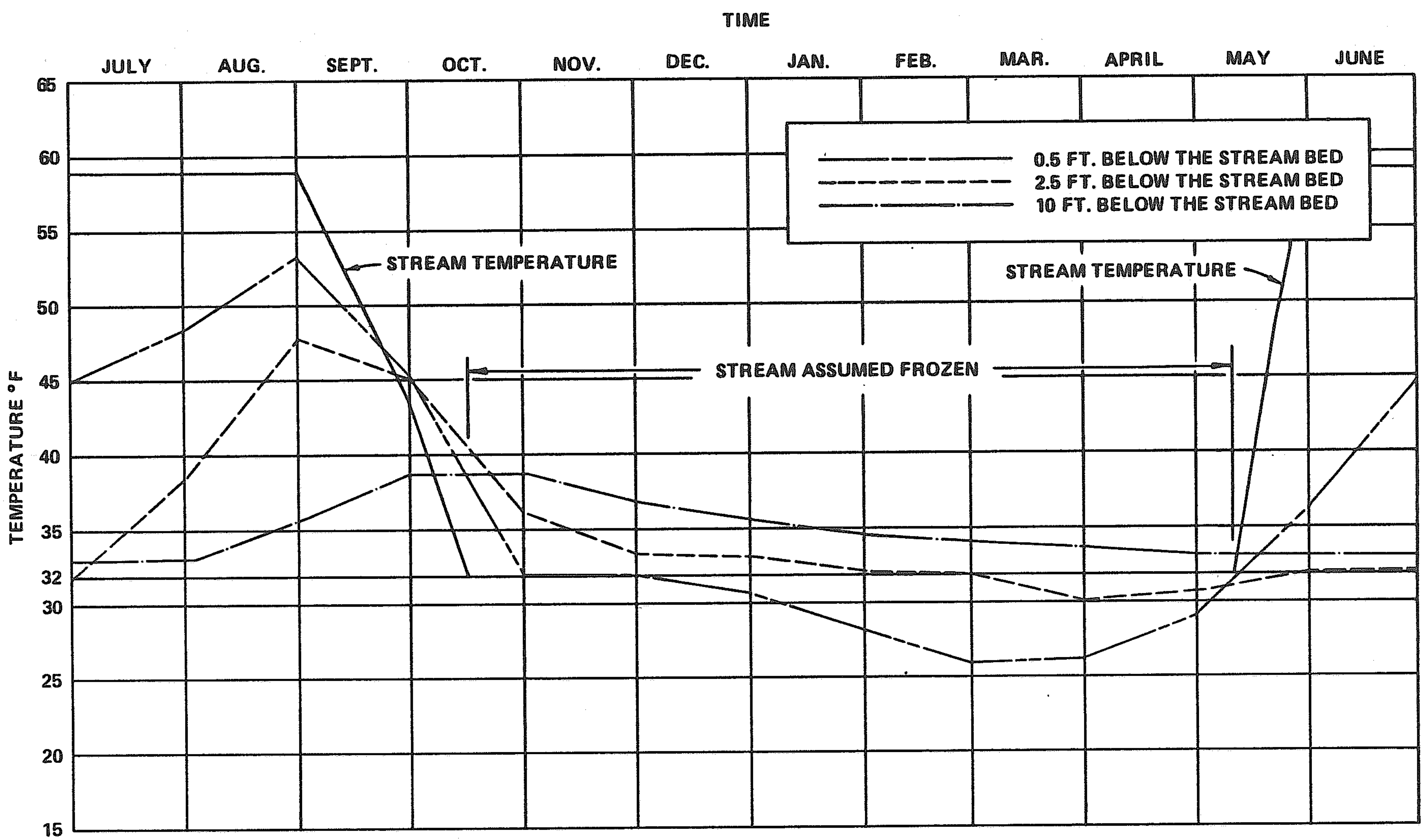
COLD STREAM TEMPERATURE
TEMPERATURE VARIATION BELOW THE STREAM BED



STREAM DEPTH = 1 FT.
STREAM FLOW RATE = 1 FT/S
GROUNDWATER STATIC

FIGURE 4 - 15

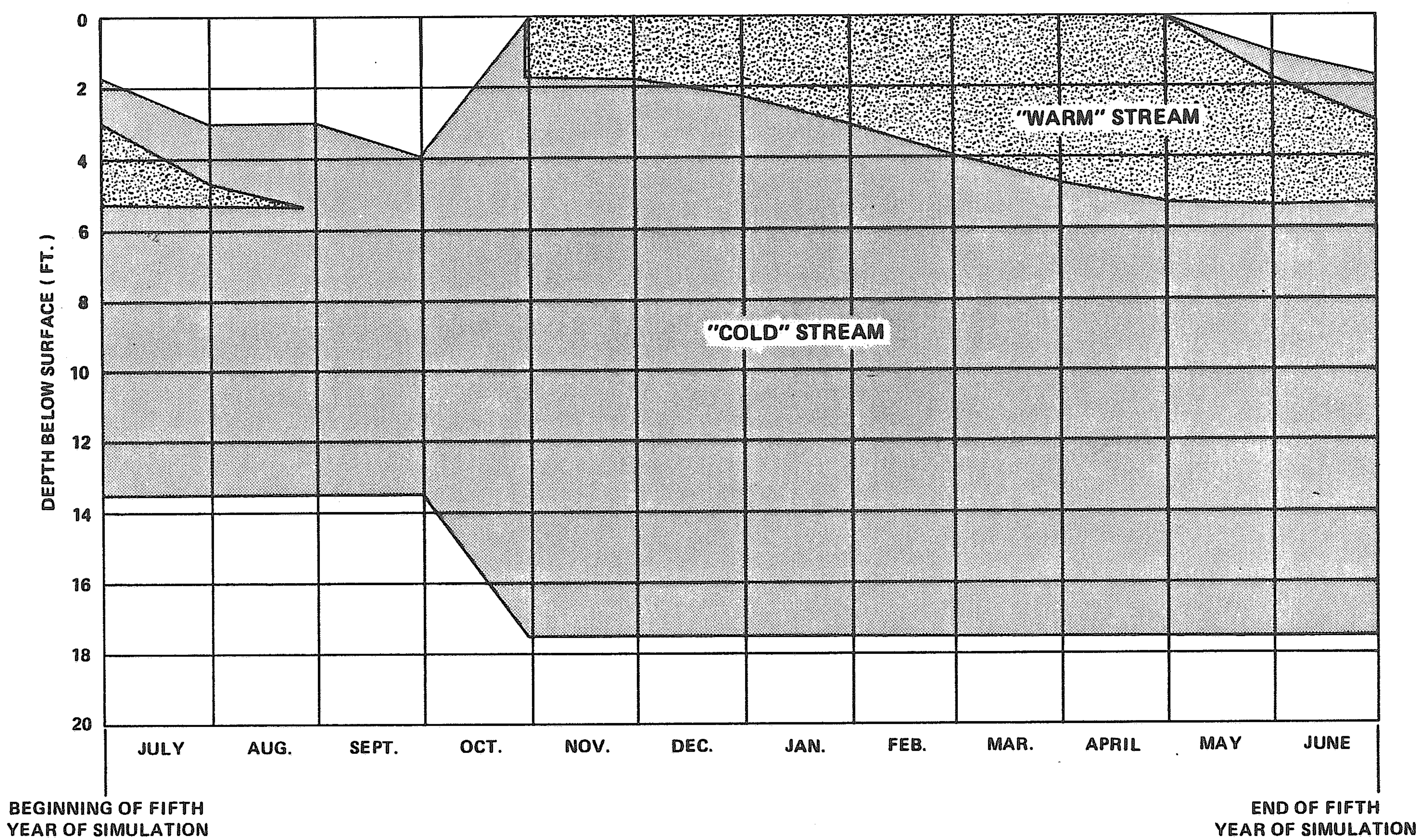
WARM STREAM TEMPERATURE
TEMPERATURE VARIATION BELOW THE STREAM BED

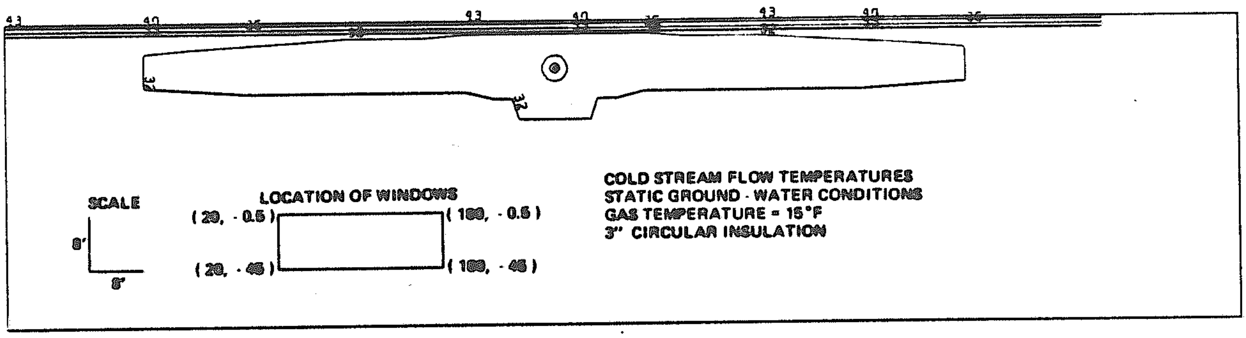


STREAM DEPTH = 1 FT.
STREAM FLOW RATE = 1 FT/S
GROUNDWATER STATIC

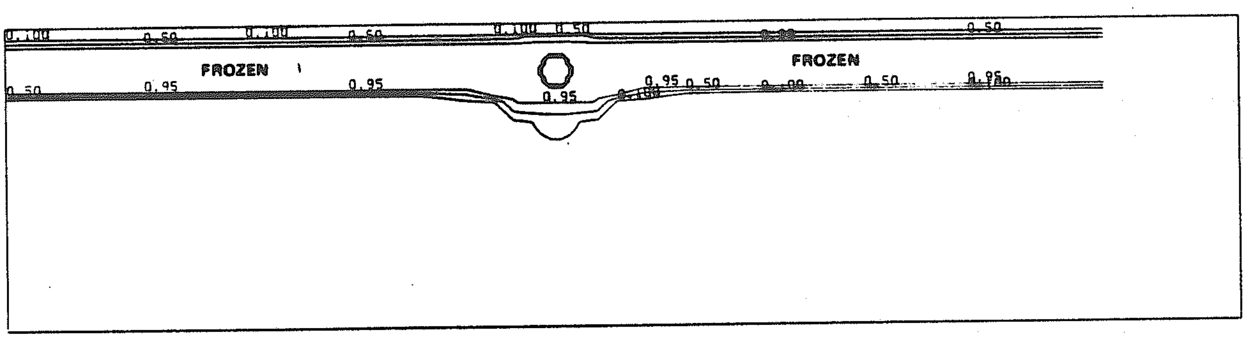
FIGURE 4 - 16

COMPARISON OF ICE FORMATION
BELOW A COLD AND A WARM STREAM ENVIRONMENT





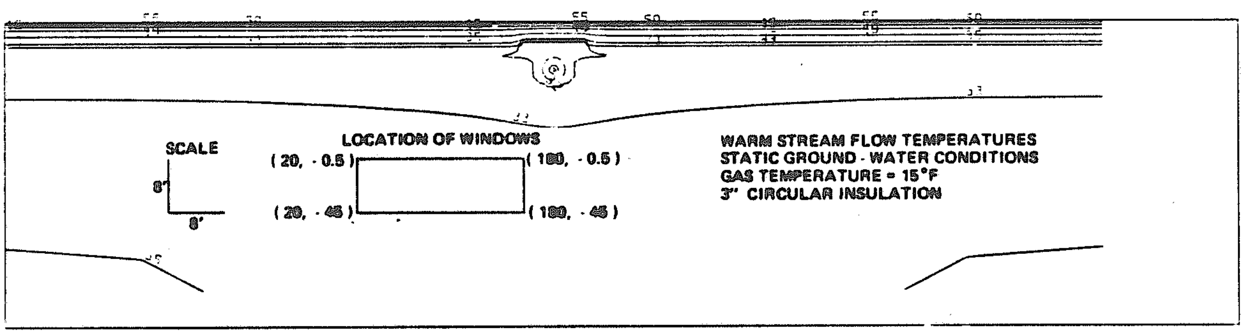
TEMPERATURE , TIME= 4.0 YRS (1460.0 D. JUL 1)(KUVCGON)



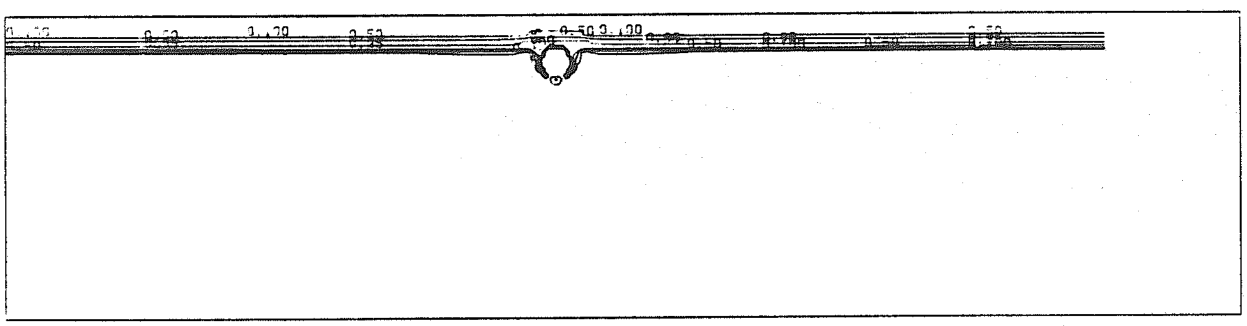
ICE CØNTENT. TIME = 4.0 YRS (1460.0 D. JUL 1)(KUVCGON)

FIGURE 4 - 17

TEMPERATURE AND ICE CONTENT PLOTS FOR INSULATED PIPELINE OPERATION BENEATH WARM STREAM



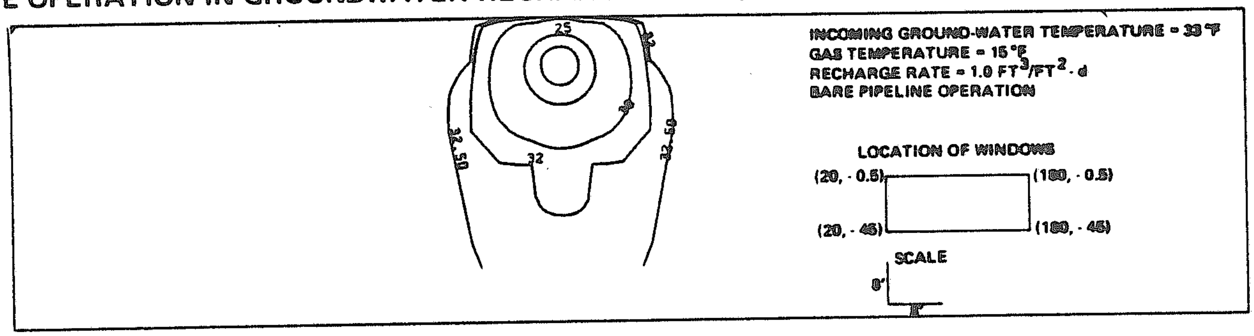
TEMPERATURE . TIME= 4.0 YRS (1460.0 D. JUL 1)(KUVKDYR)



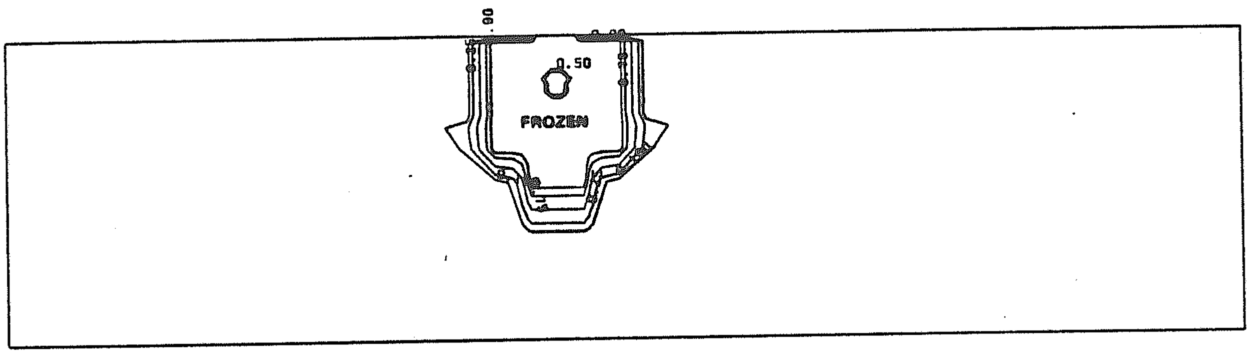
ICE CØNTENT. TIME = 4.0 YRS (1460.0 D. JUL 1)(KUVKDYR)

FIGURE 4 - 18

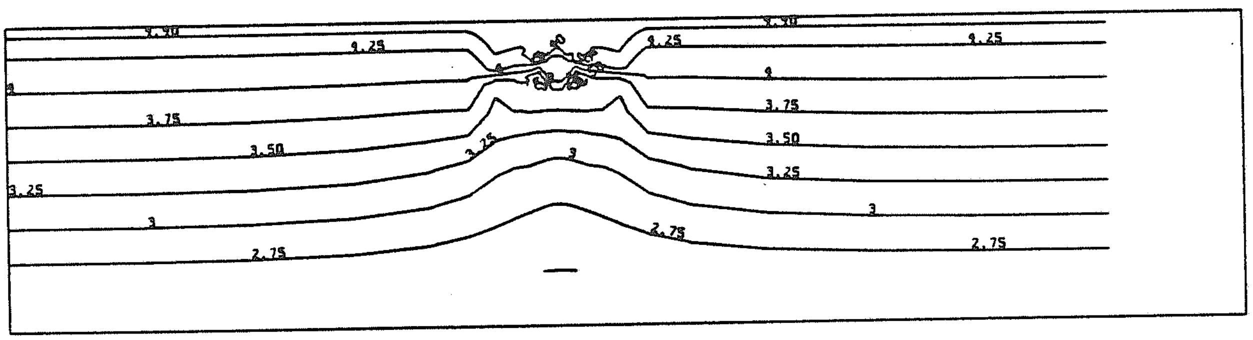
TEMPERATURE, ICE CONTENT, HYDRAULIC HEAD AND GROUNDWATER VECTOR PLOTS FOR BARE PIPE OPERATION IN GROUNDWATER RECHARGE AREA (CONTOUR INTERVALS ARE VARIABLE)



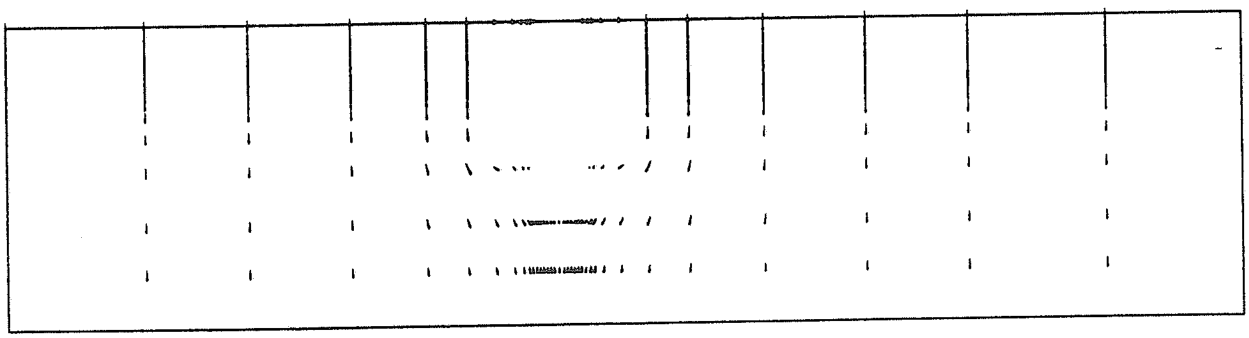
TEMPERATURE . TIME= 4.0 YRS (1460.0 D. JUL 1)(KUVKEØR)



ICE CØNTENT. TIME = 4.0 YRS (1460.0 D. JUL 1)(KUVKEØR)



TØTAL HEAD . TIME= 4.0 YRS (1460.0 D. JUL 1)(KUVKEØR)

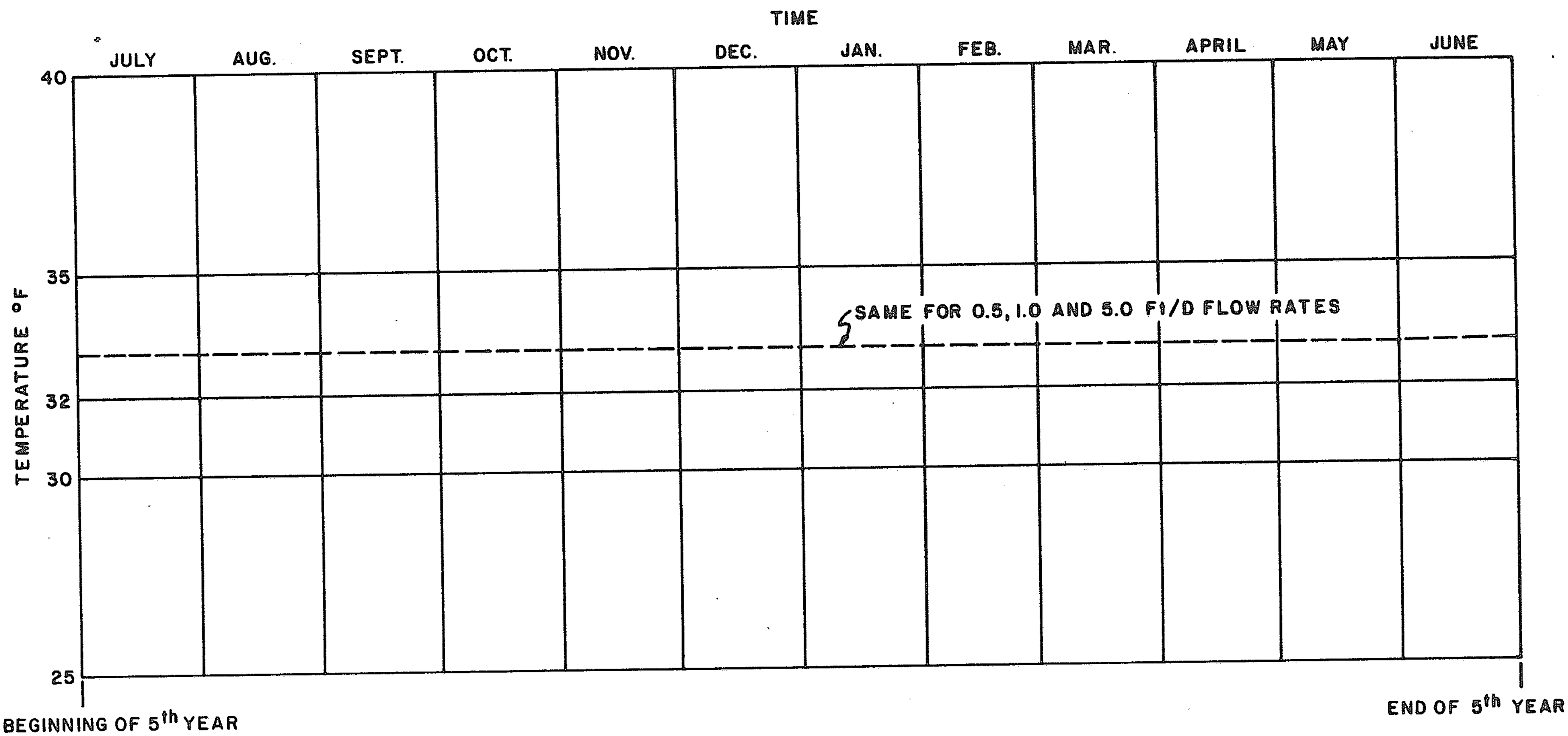


GRØUND-WATER FLØW VECTØRS. TIME= 4.0 YRS (1460.0 D. JUL 1)(KUVKEØR)
VECTØR SCALE: 1.03E+01 UNITS/PLØT INCH

FIGURE 4-19

FIGURE 4 - 20

GROUNDWATER DISCHARGE
VARIATION IN TEMPERATURE 2.4 FEET BELOW THE BASE OF THE SURFACE WATER BODY
INCOMING GROUND-WATER TEMPERATURE = 33.0° F



GROUNDWATER DISCHARGE
GROUNDWATER IS 1.0 $FT^3/FT^2 \cdot d$
INCOMING GROUNDWATER TEMPERATURE IS 40°F

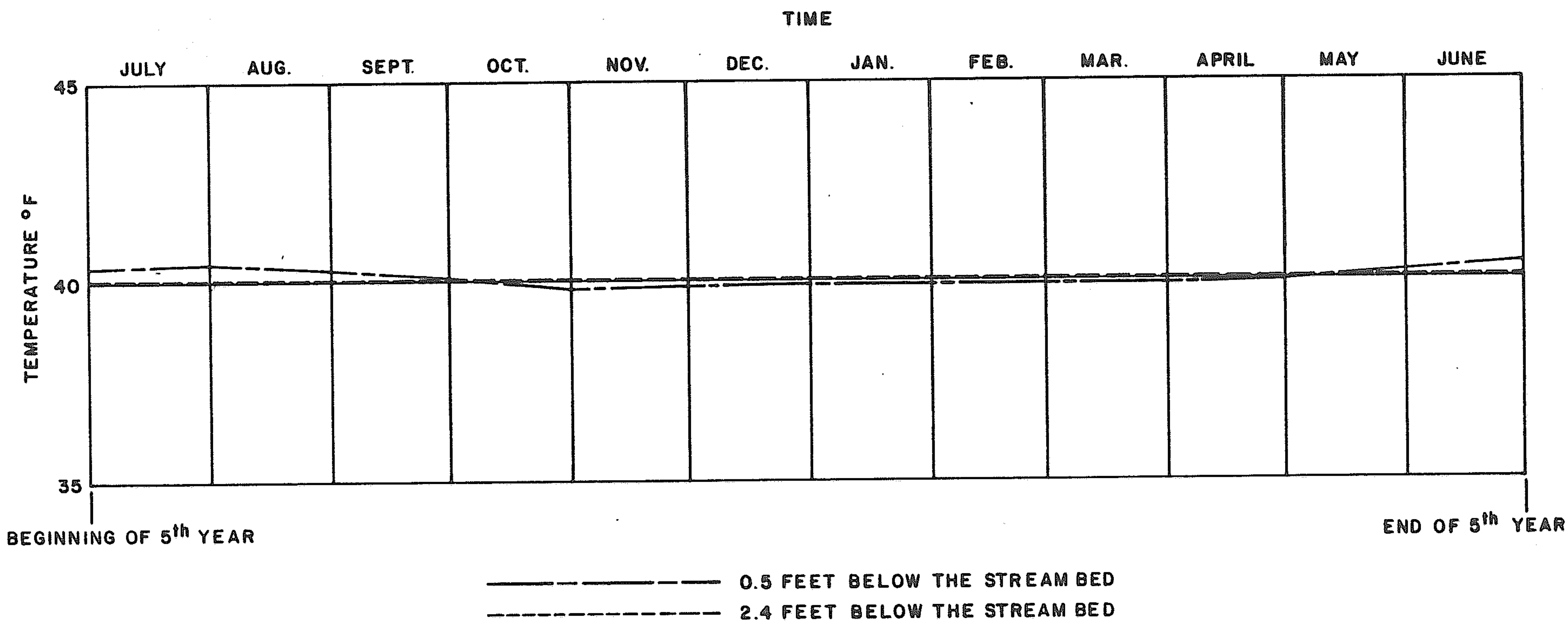


FIGURE 4-21

GROUNDWATER DISCHARGE
VARIATION IN TEMPERATURE 0.5 FEET BELOW THE BASE OF THE SURFACE WATER BODY
INCOMING GROUNDWATER TEMPERATURE = 33.0 F

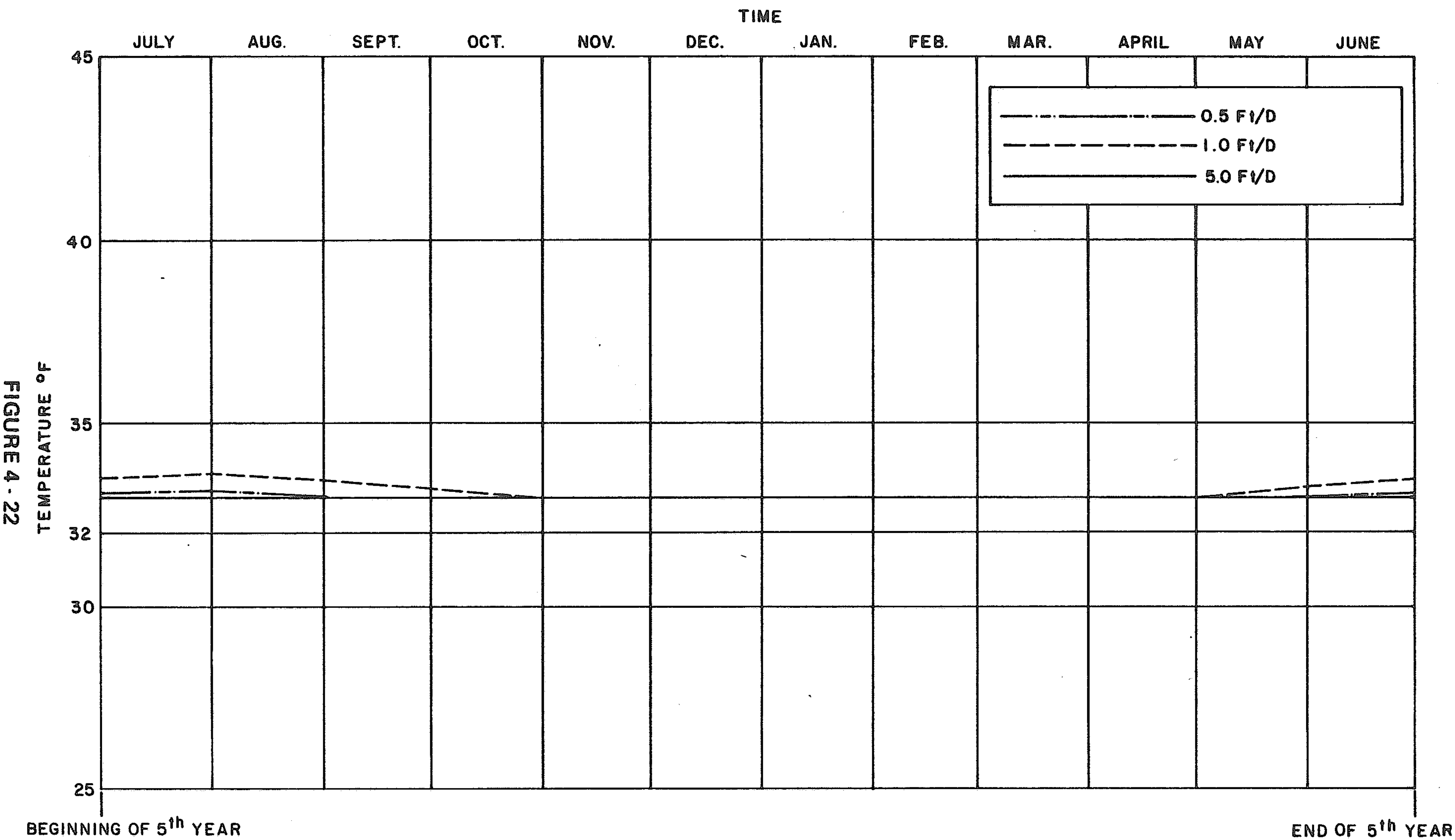
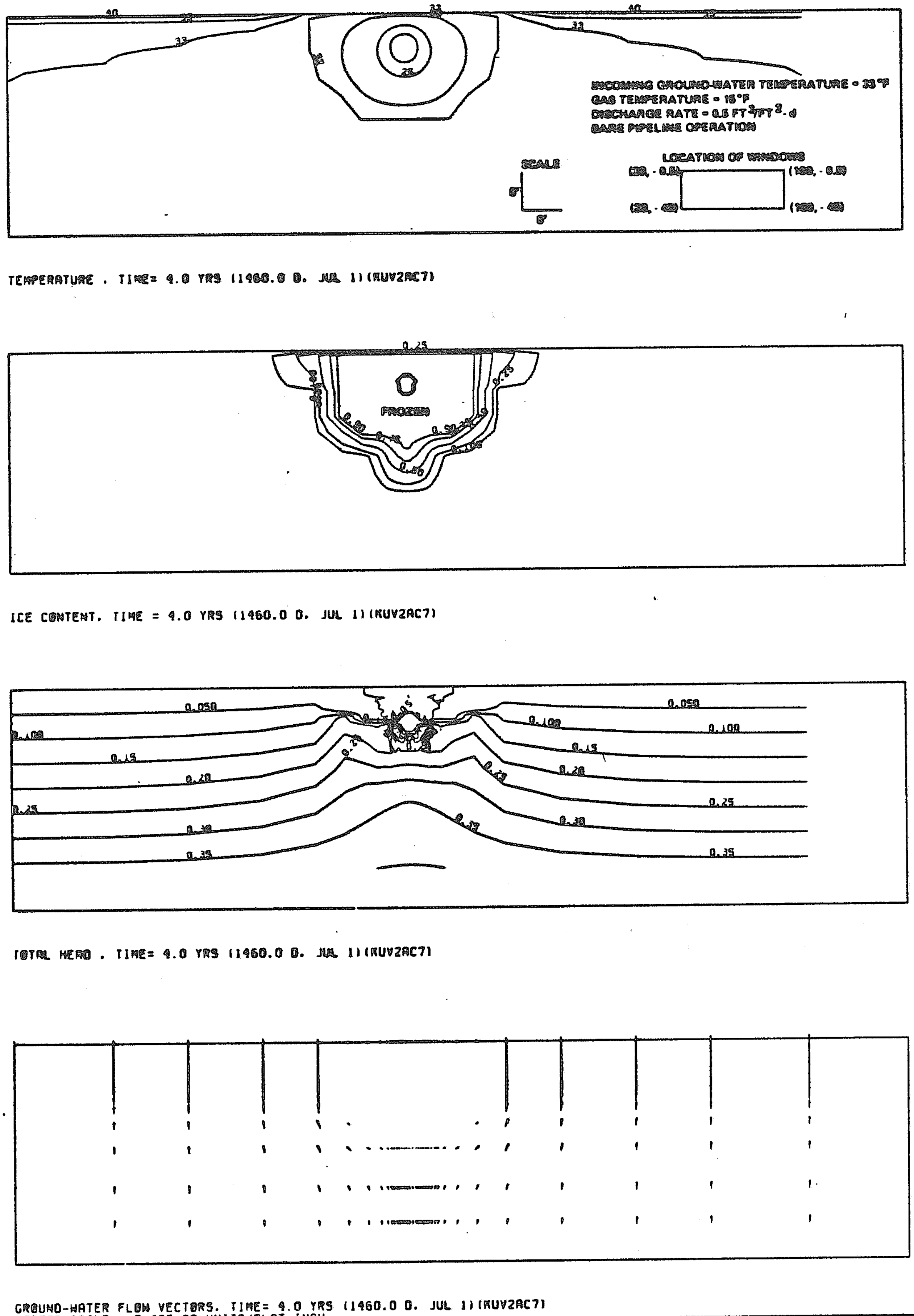


FIGURE 4 - 22

CHILLED PIPE EFFECTS ON STREAMS

TEMPERATURE, ICE CONTENT, HYDRAULIC HEAD AND GROUNDWATER VECTOR PLOTS FOR BARE PIPE OPERATION IN A GROUNDWATER DISCHARGE AREA (CONTOUR INTERVALS ARE VARIABLE)



VECTOR SCALE 5.35E-00 UNITS/PLOT INCH

FIGURE 4 - 23

LATERAL FLOW
TEMPERATURE VARIATION
AT 0.5 FEET BELOW THE BASE OF THE SURFACE WATER BODY
100 FEET FROM UPSTREAM BOUNDARY
INCOMING GROUND-WATER TEMPERATURE = 33° F

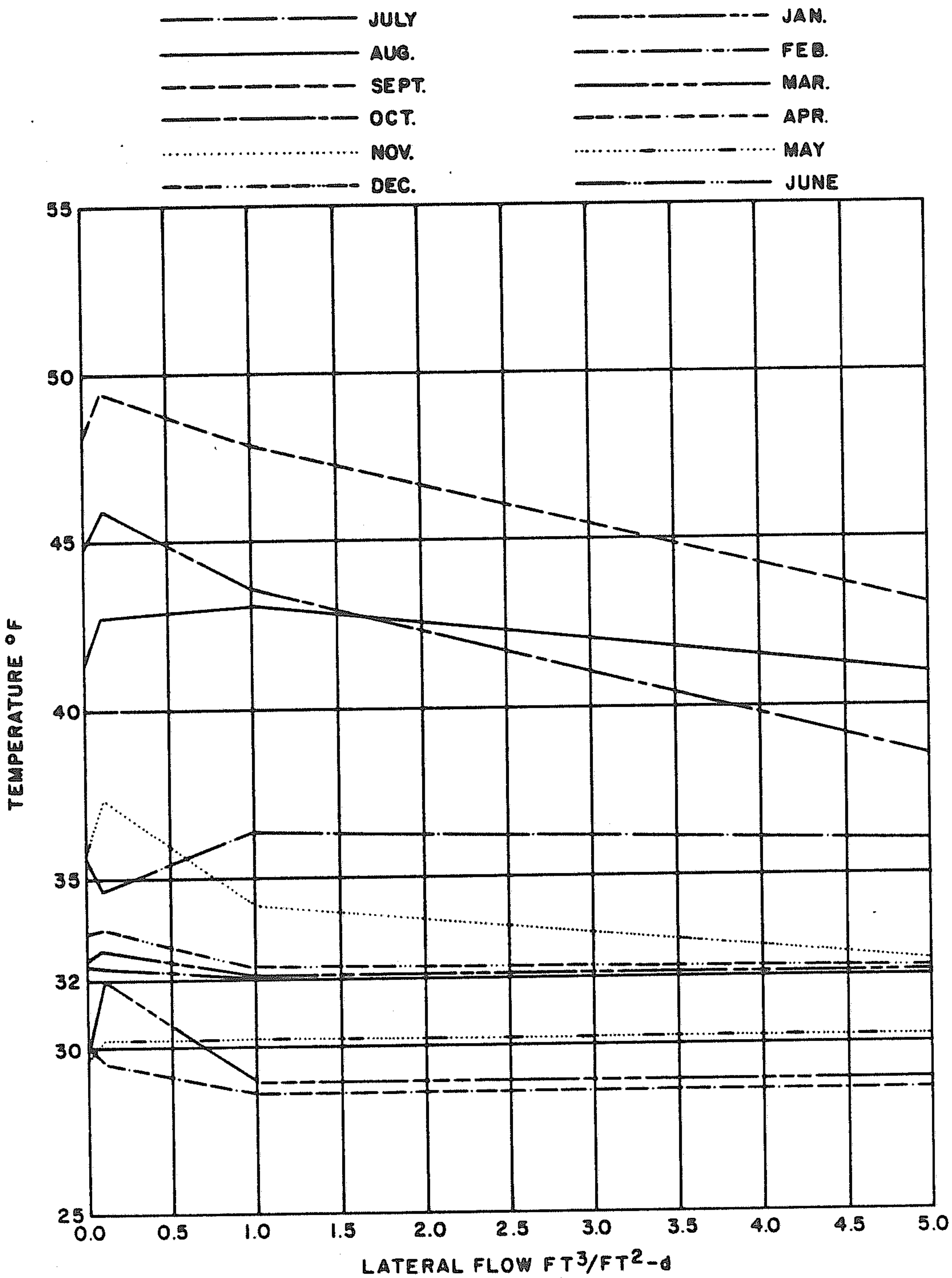


FIGURE 4 - 24

LATERAL FLOW
TEMPERATURE VARIATION AT 2.4 FEET BELOW THE BASE OF THE SURFACE WATER BODY
100 FEET FROM UPSTREAM BOUNDARY
INCOMING GROUNDWATER TEMPERATURE = 33 °F

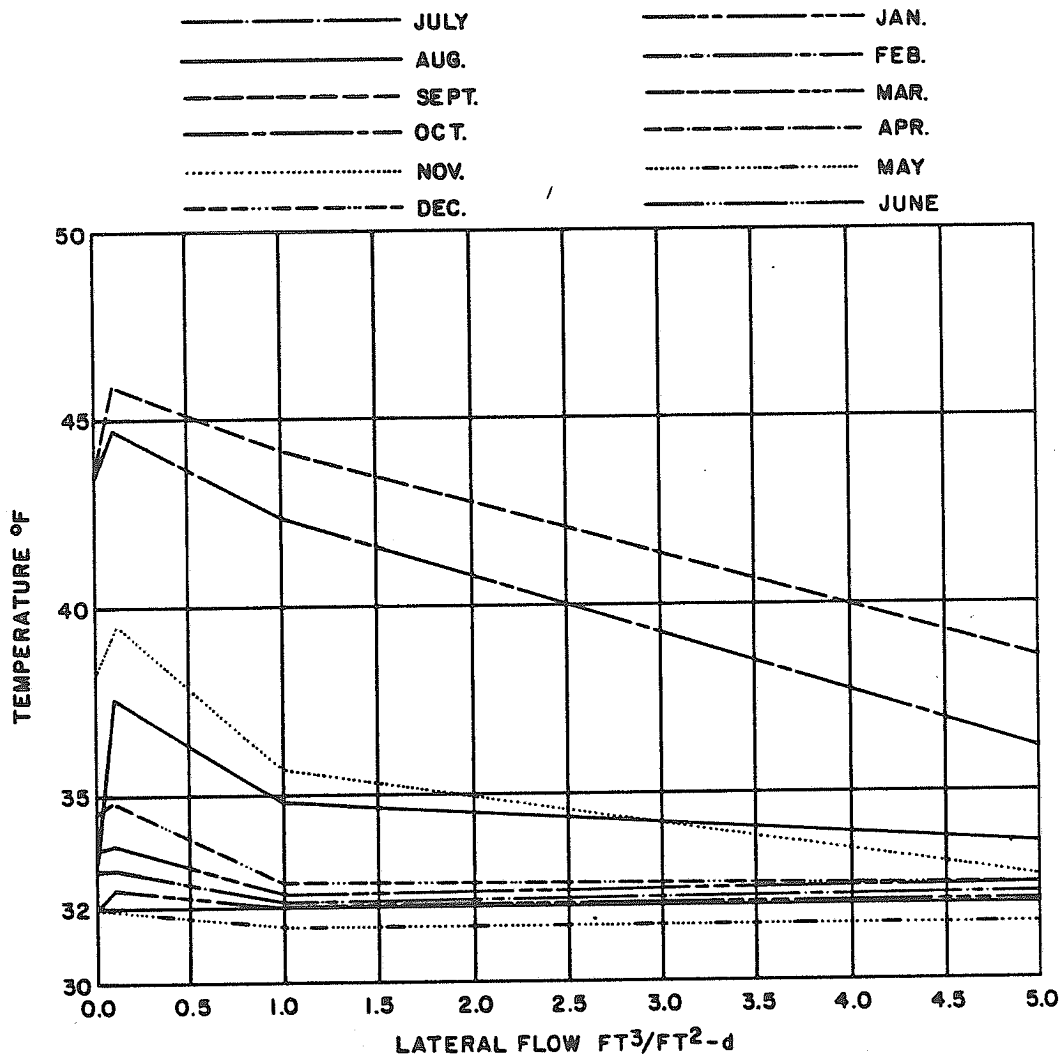


FIGURE 4 - 25

LATERAL FLOW
TEMPERATURE VARIATION AT 9.8 FEET BELOW THE BASE OF THE SURFACE WATER BODY
100 FEET FROM UPSTREAM BOUNDARY
INCOMING GROUNDWATER TEMPERATURE = 33 °F

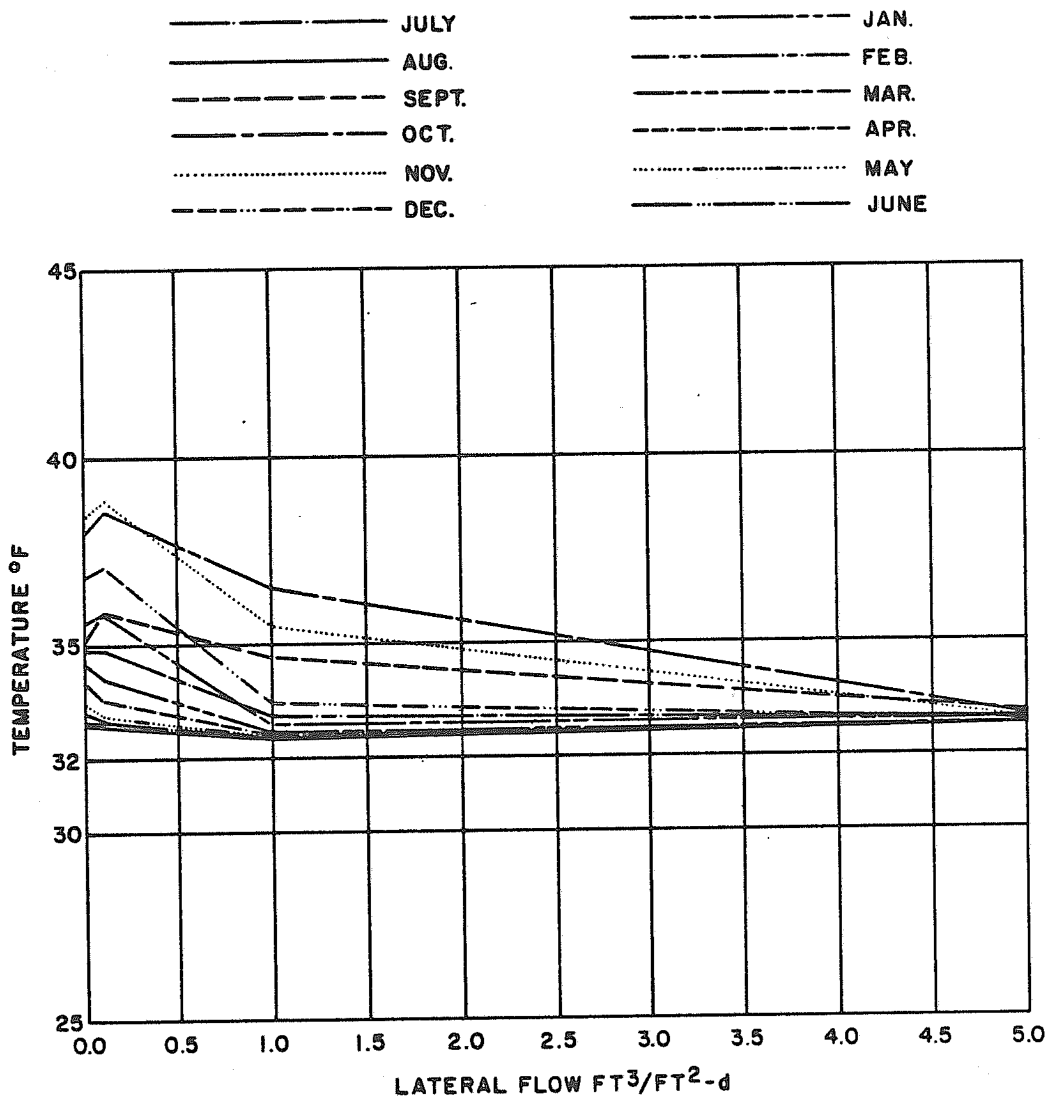
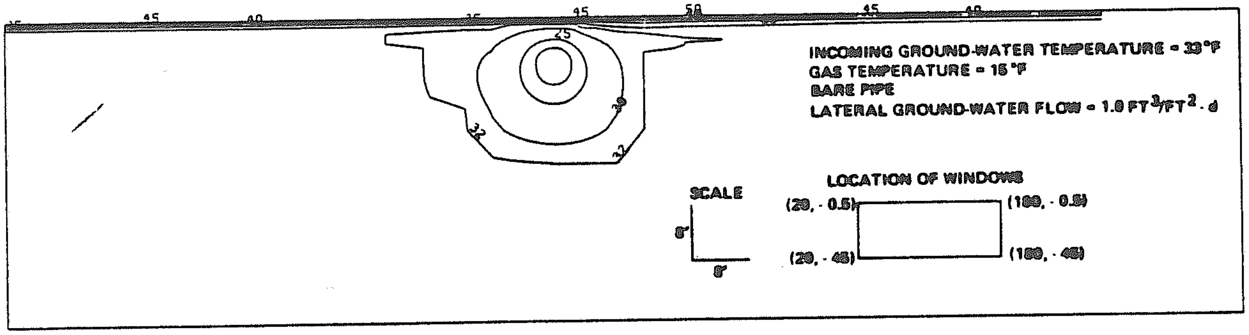
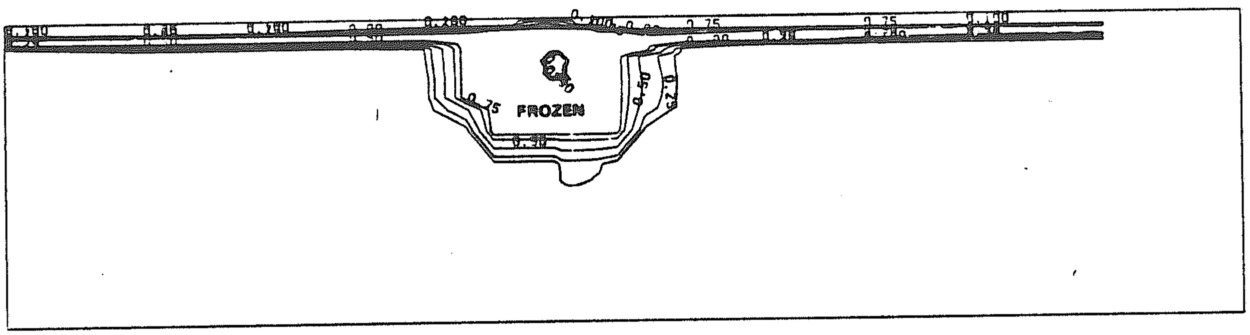


FIGURE 4 - 26

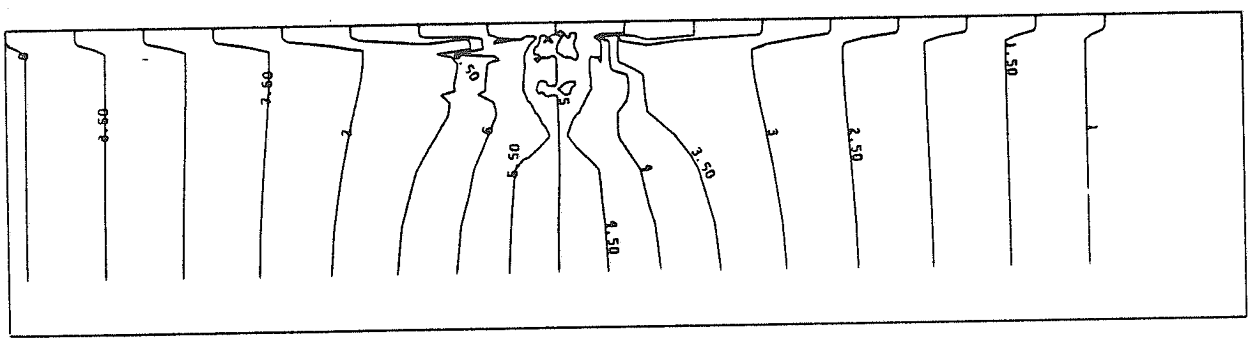
TEMPERATURE, ICE CONTENT, HYDRAULIC HEAD AND GROUNDWATER FLOW VECTORS FOR BARE PIPE OPERATION IN A LATERAL FLOW AREA. GROUNDWATER FLOW = 1 FT³/FT² -d (CONTOUR INTERVALS ARE VARIABLE)



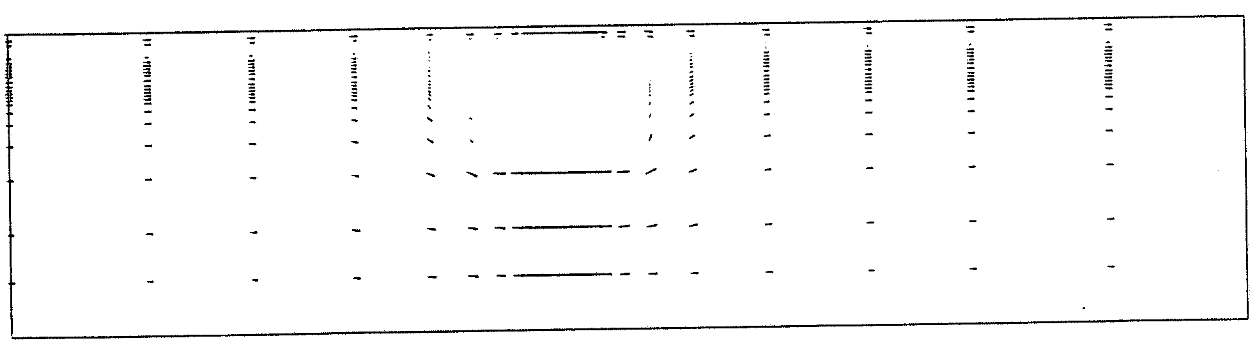
TEMPERATURE . TIME= 4.0 YRS (1460.0 D. JUL 1)(KUVYA77)



ICE CONTENT. TIME = 4.0 YRS (1460.0 D. JUL 1)(KUVYA77)



TOTAL HEAD . TIME= 4.0 YRS (1460.0 D. JUL 1)(KUVYA77)



TOTAL HEAD . TIME= 4.0 YRS (1460.0 D. JUL 1)(KUVYA77)
VECTOR SCALE 1.43E+01 UNITS/PLOT INCH

FIGURE 4 - 27

TEMPERATURE, ICE CONTENT, HYDRAULIC HEAD AND GROUNDWATER FLOW VECTORS FOR INSULATED PIPE OPERATION IN A LATERAL GROUNDWATER FLOW AREA GROUNDWATER FLOW = 1 $FT^3/FT^2 \cdot d$ (CONTOUR INTERVALS ARE VARIABLE)

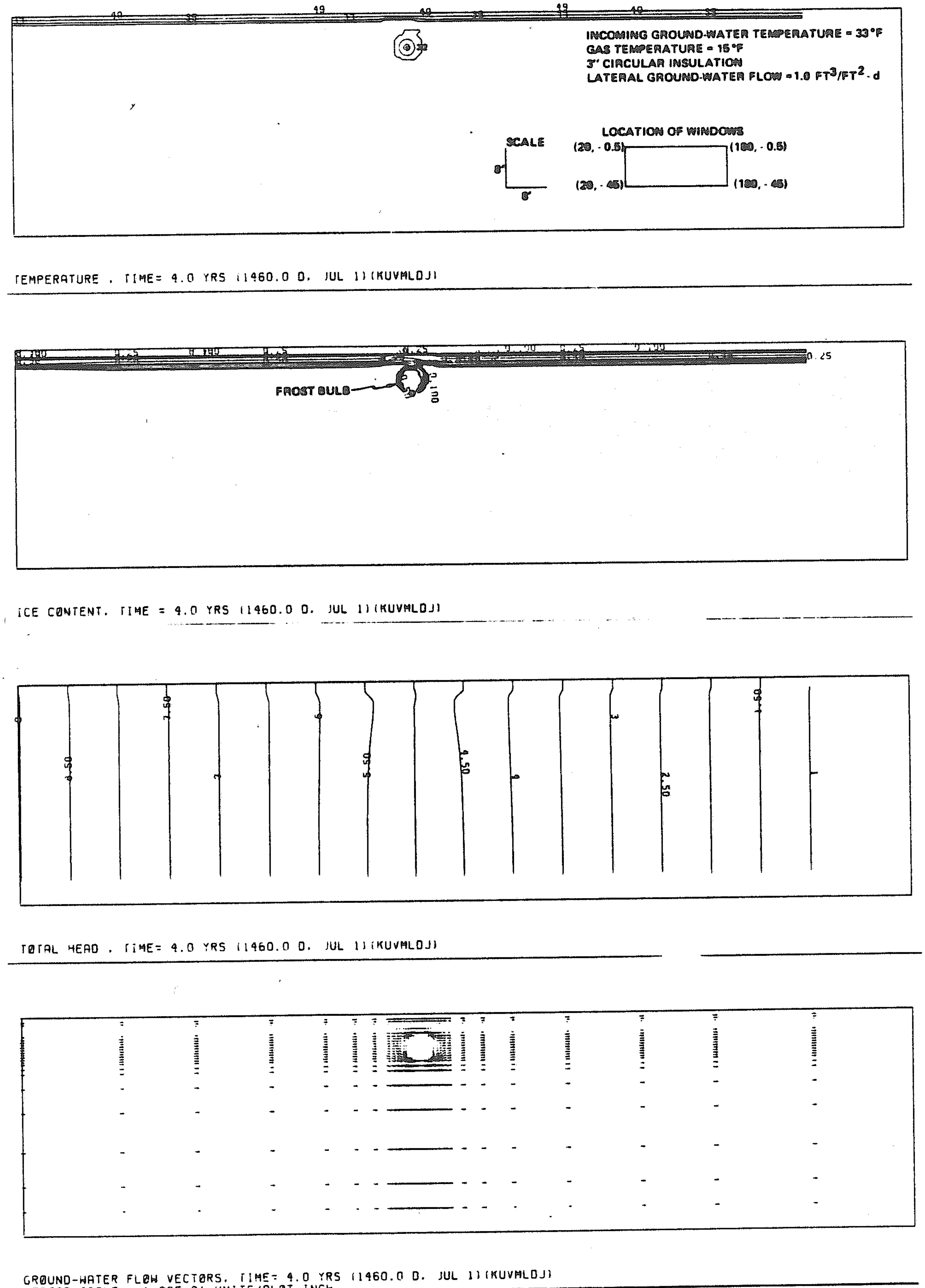
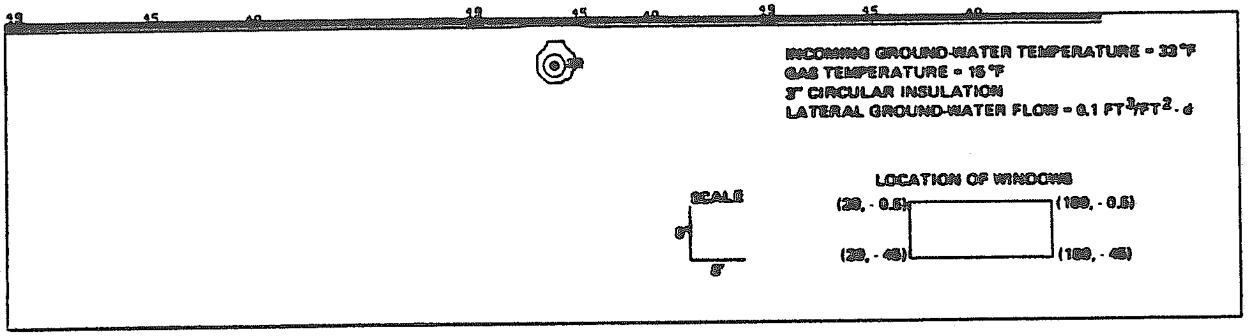
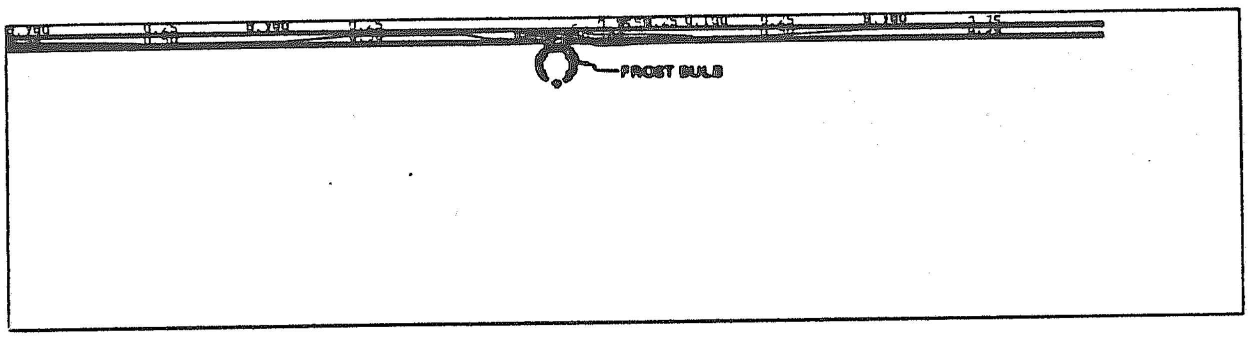


FIGURE 4-28

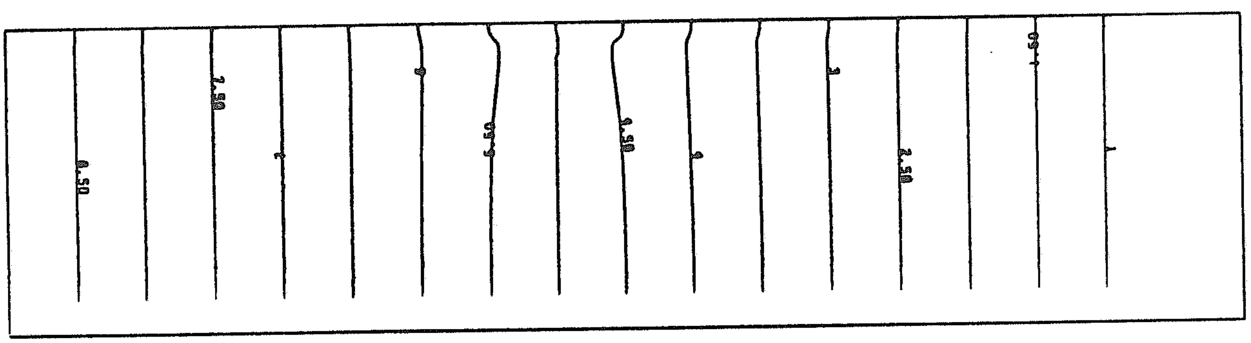
TEMPERATURE, ICE CONTENT, HYDRAULIC HEAD AND GROUNDWATER FLOW VECTORS FOR INSULATED PIPE OPERATION IN A LATERAL GROUNDWATER FLOW AREA. GROUNDWATER FLOW = 0.1 FT^3/FT^2 - d (CONTOUR INTERVALS ARE VARIABLE)



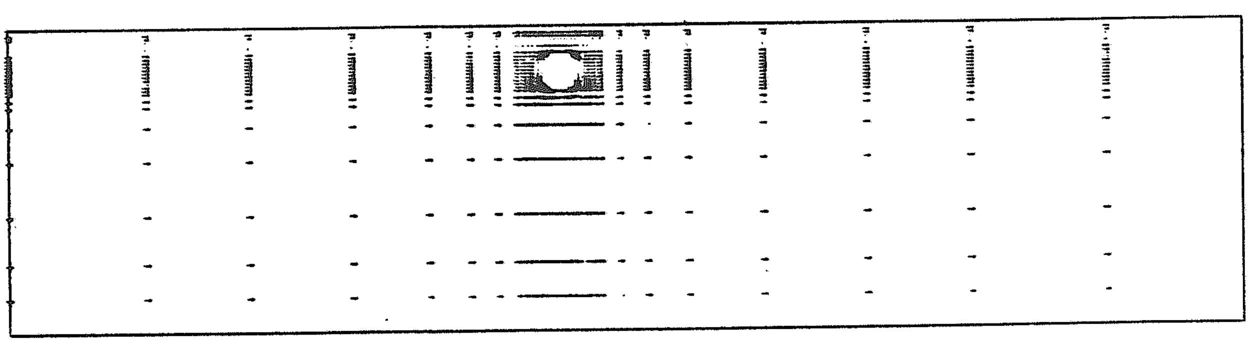
TEMPERATURE . TIME= 4.0 YRS (1460.0 D. JUL 1)(KUVYASZ)



ICE CONTENT. TIME = 4.0 YRS (1460.0 D. JUL 1)(KUVYASZ)



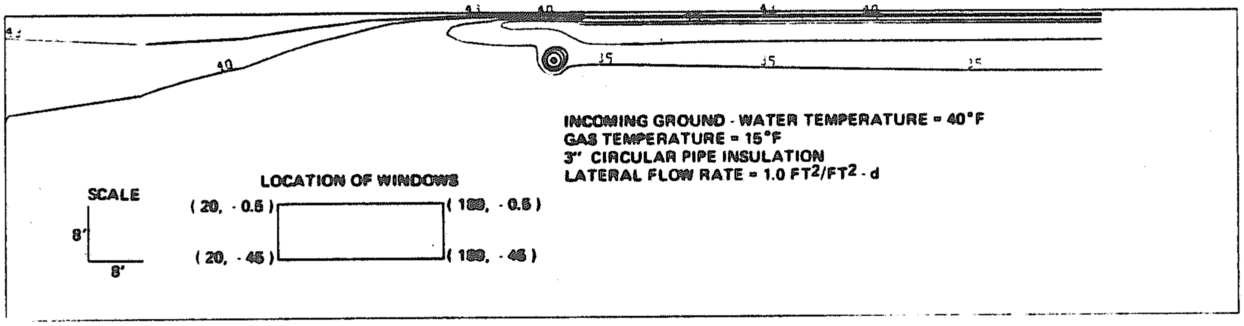
TOTAL HEAD . TIME= 4.0 YRS (1460.) D. JUL 1)(KUVYASZ)



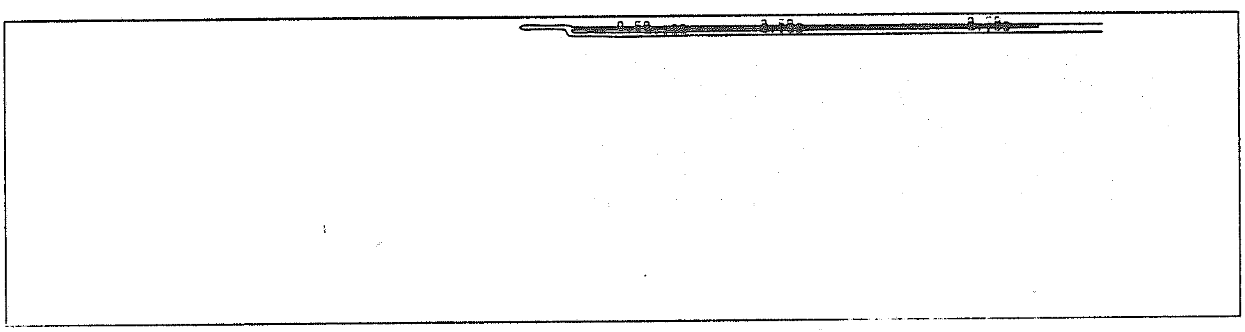
GROUND-WATER FLOW VECTORS. TIME= 4.0 YRS (1460.) . JUL 1)(KUVYASZ)
VECTOR SCALE 1.65E+00 UNITS/PLOT INCH

FIGURE 4 - 29

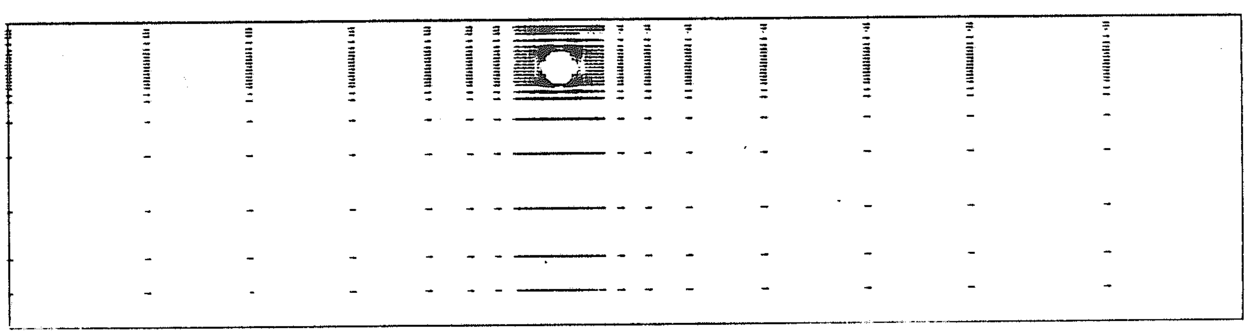
TEMPERATURE, ICE CONTENT AND GROUNDWATER FLOW VECTOR PLOTS FOR INSULATED PIPE OPERATION IN A LATERAL GROUNDWATER FLOW AREA. GROUNDWATER FLOW = 1.0 FT.^{3}/FT.^{2} - d, GROUNDWATER TEMPERATURE = 40° F



TEMPERATURE . TIME= 4.0 YRS (1460.0 D. JUL 1)(1NLK62)



ICE CØNTENT. TIME = 4.0 YRS (1460.0 D. JUL 1)(1NLK62)



GRØUND-WATER FLØW VECTØRS. TIME= 4.0 YRS (1460.0 D. JUL 1)(1NLK62)

FIGURE 4 - 30

TEMPERATURE, ICE CONTENT, HYDRAULIC HEAD AND GROUNDWATER FLOW VECTORS FOR UNDISTURBED CONDITIONS. HYDRAULIC CONDUCTIVITY INCREASES WITH DEPTH
(CONTOUR INTERVALS ARE VARIABLE)

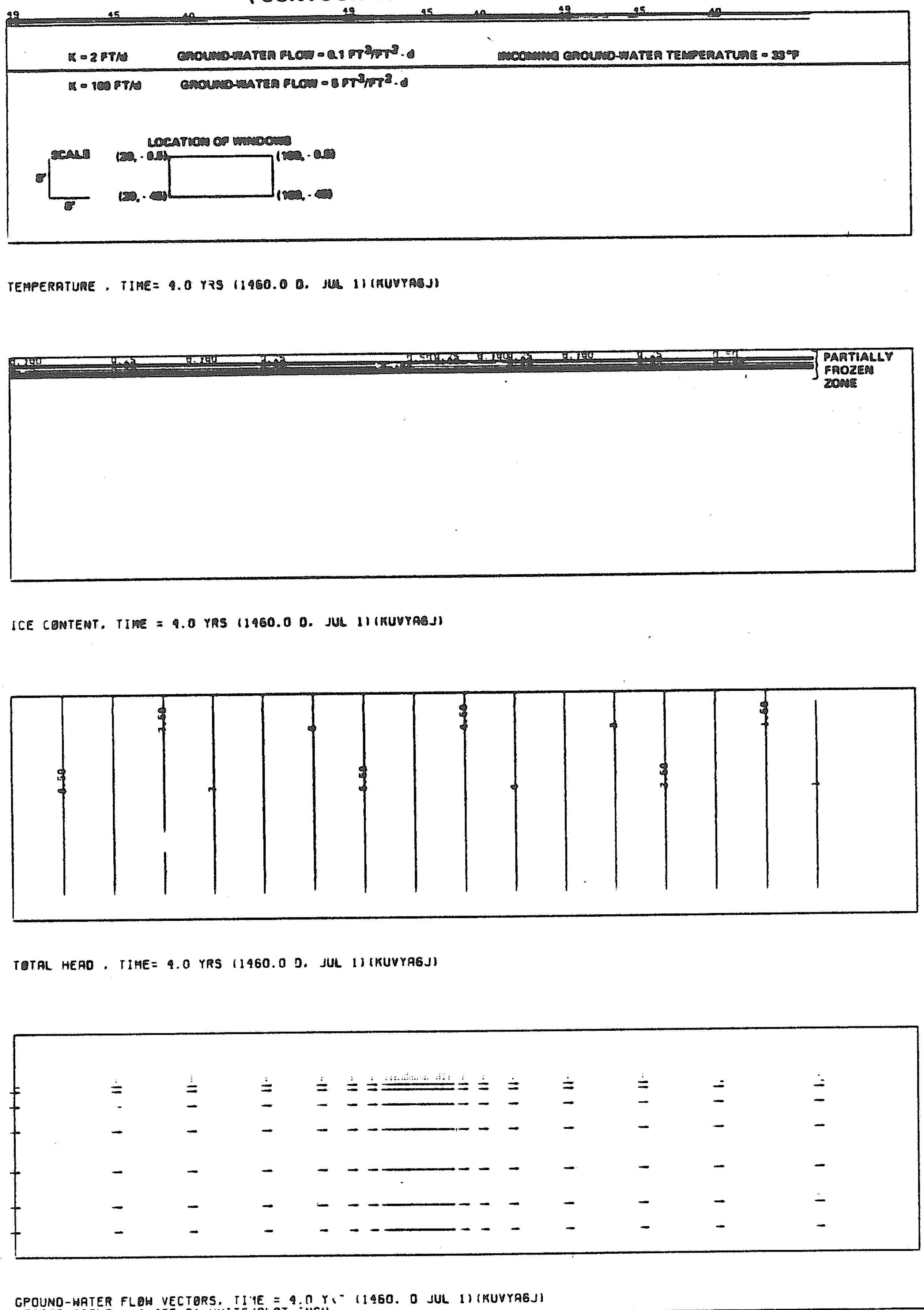
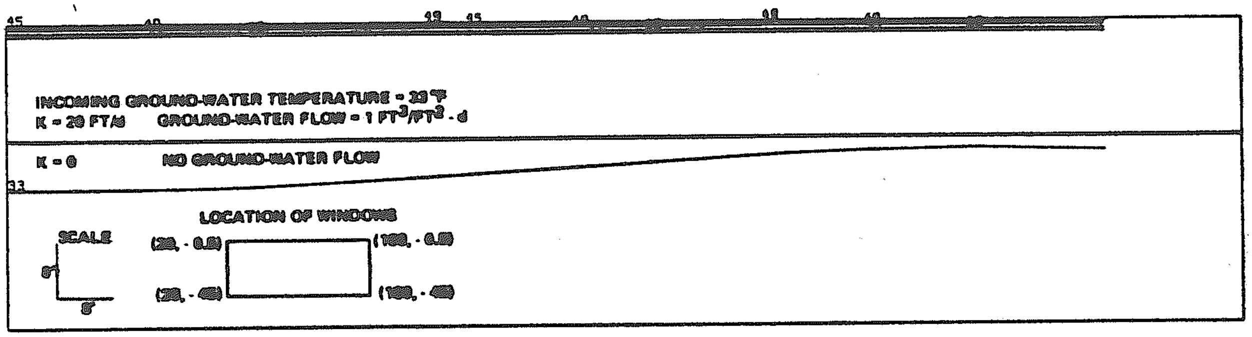
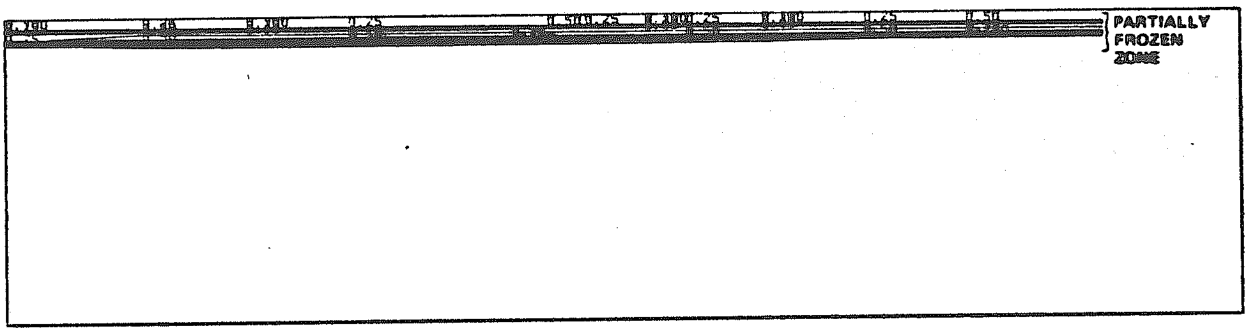


FIGURE 4 - 31

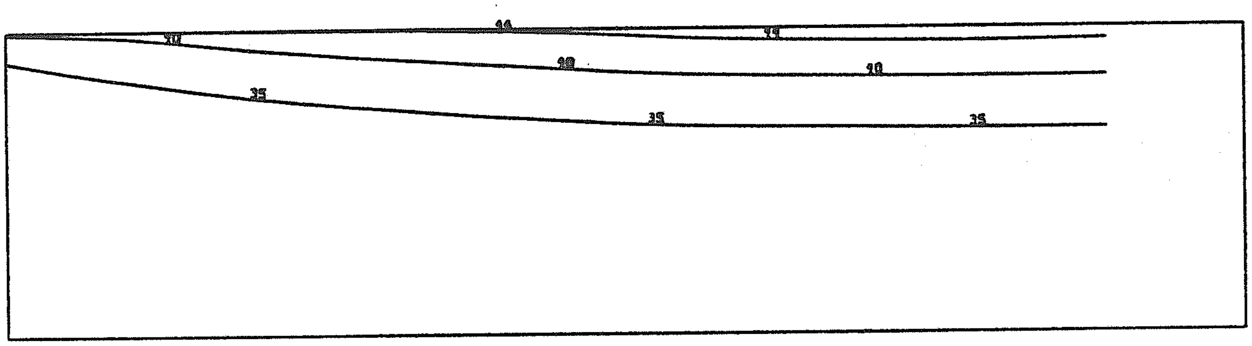
TEMPERATURE, ICE CONTENT AND HYDRAULIC HEAD PLOTS FOR UNDISTURBED CONDITIONS, HYDRAULIC CONDUCTIVITY INCREASES WITH DEPTH (CONTOUR INTERVALS ARE VARIABLE)



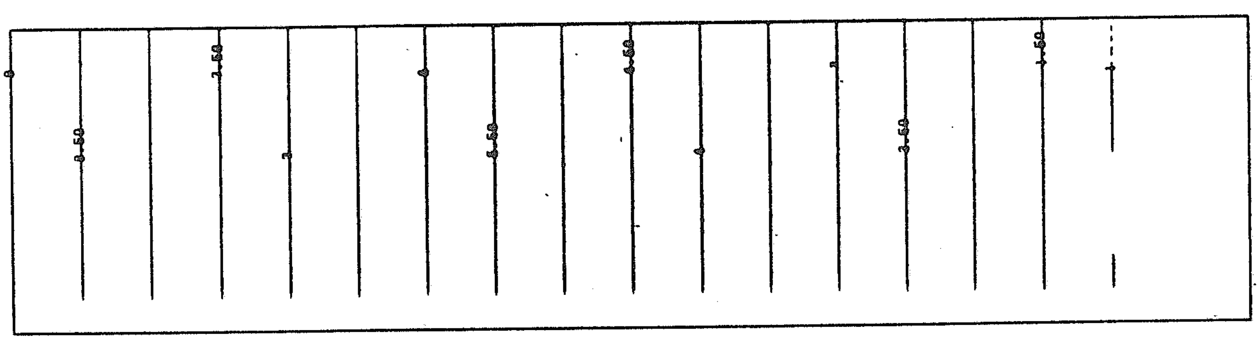
TEMPERATURE . TIME= 5.0 YRS (1825.1 D. JUL 1)(KUVKB3R)



ICE CONTENT . TIME= 5.0 YRS (1825.1 D. JUL 1)(KUVKB3R)



TEMPERATURE . TIME= 4.25 YRS (1551.3 D. OCT 1)(KUVKB3R)



TOTAL HEAD . TIME= 4.25 YRS (1551.3 D. OCT 1)(KUVKB3R)

FIGURE 4 - 32

TEMPERATURE, ICE CONTENT, HYDRAULIC HEAD AND GROUNDWATER FLOW VECTORS FOR INSULATED PIPE OPERATION. HYDRAULIC CONDUCTIVITY DECREASES WITH DEPTH (CONTOUR INTERVALS ARE VARIABLE)

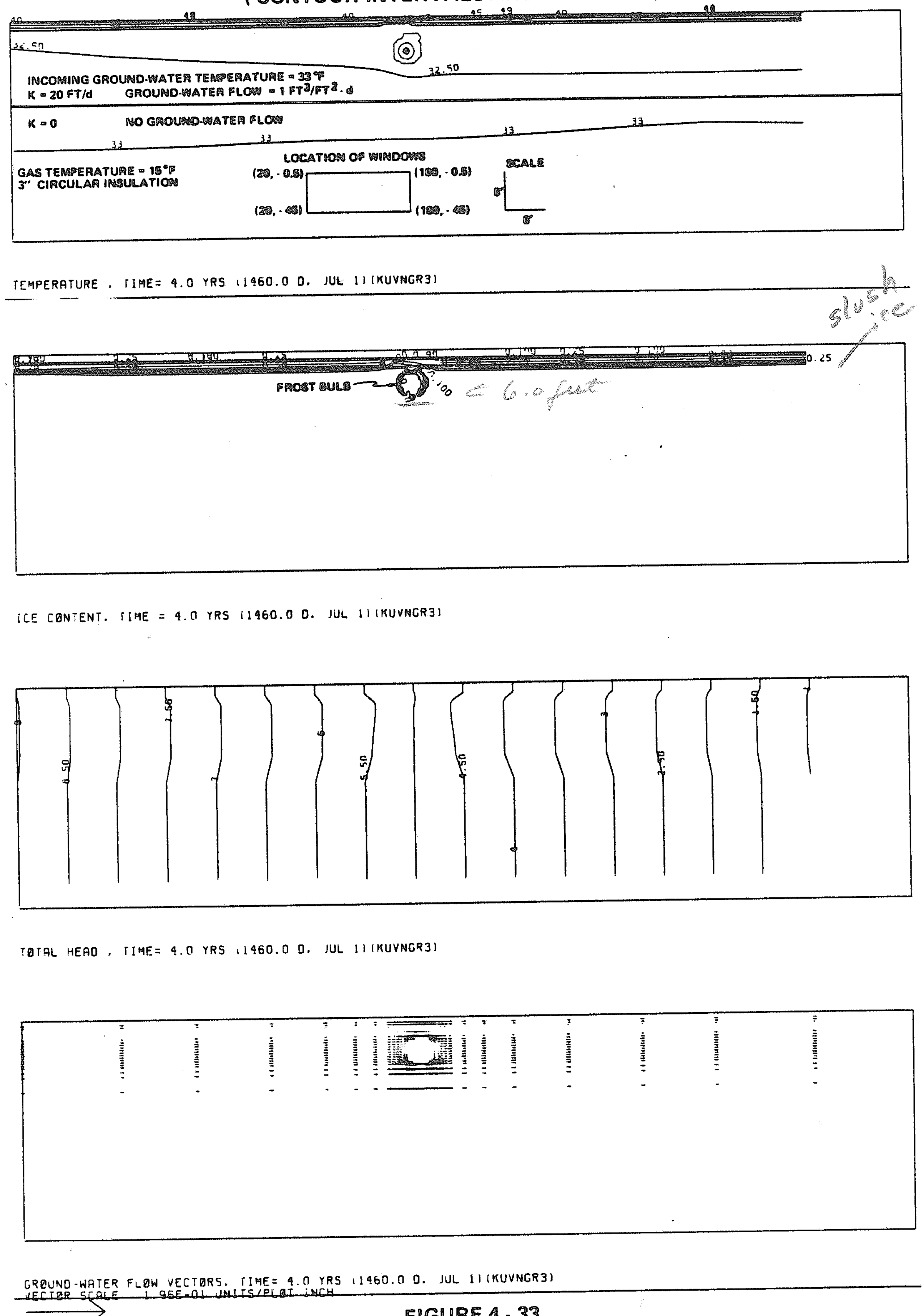
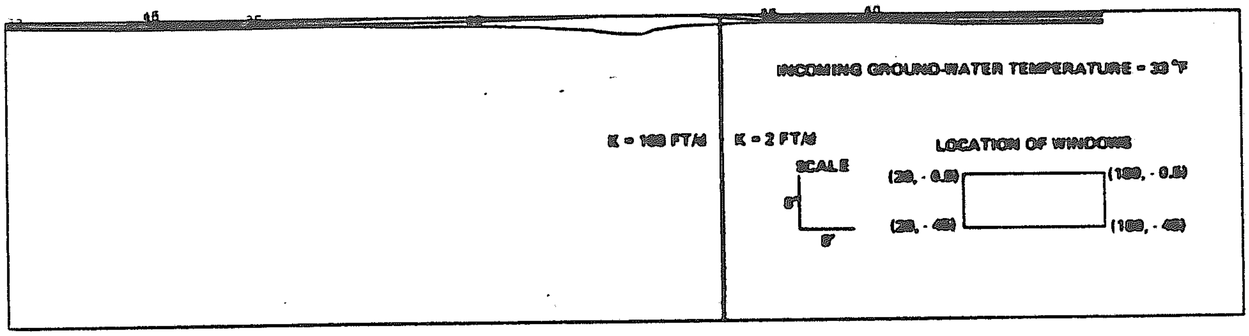
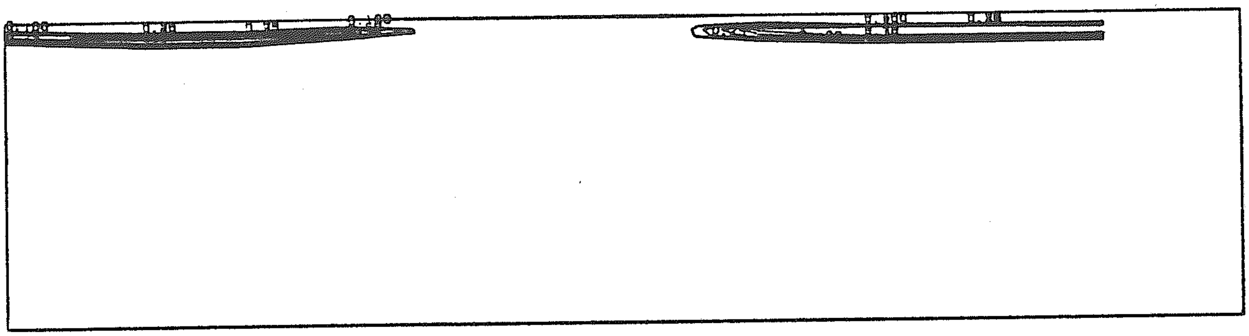


FIGURE 4 - 33

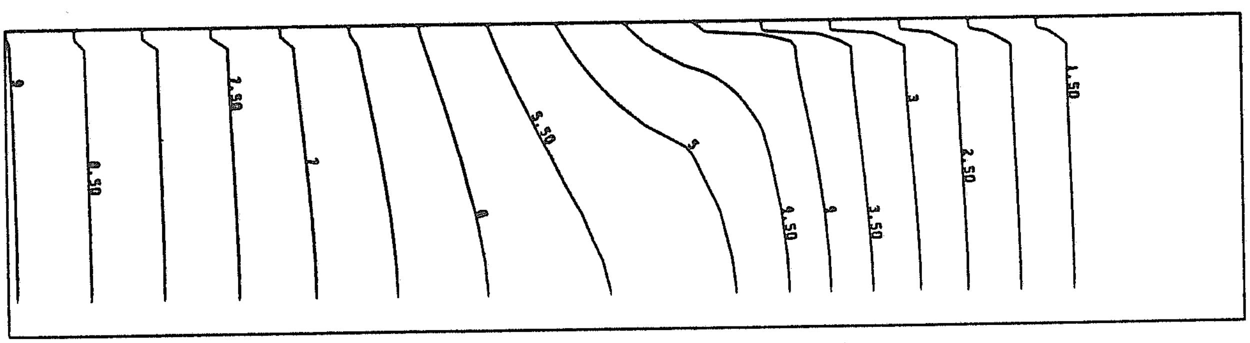
TEMPERATURE, ICE CONTENT, HYDRAULIC HEAD AND GROUNDWATER FLOW VECTORS FOR UNDISTURBED CONDITIONS. HYDRAULIC CONDUCTIVITY DECREASES DOWNSTREAM
(CONTOUR INTERVALS ARE VARIABLE)



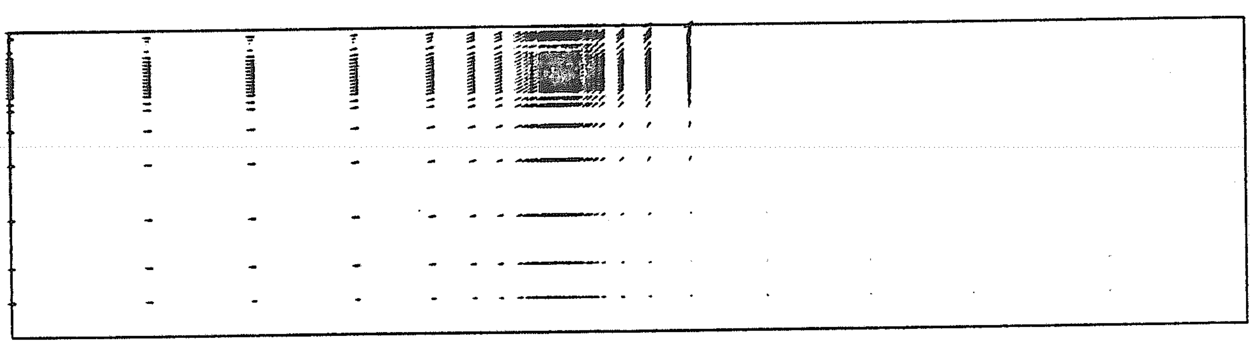
TEMPERATURE . TIME= 4.0 YRS (1460.0 D. JUL 1)(KUVYA6N)



ICE CONTENT. TIME = 4.0 YRS (1460.0 D. JUL 1)(KUVYA6N)



TOTAL HEAD . TIME= 4.0 YRS (1460.0 D. JUL 1)(KUVYA6N)



GROUND-WATER FLOW VECTORS. TIME = 4.0 YRS (1460. D JUL 1)(KUVYA6N)
VECTOR SCALE = 7.24E+01 UNITS/PLOT INCH

FIGURE 4 - 34

DESIGN LOGIC DIAGRAM

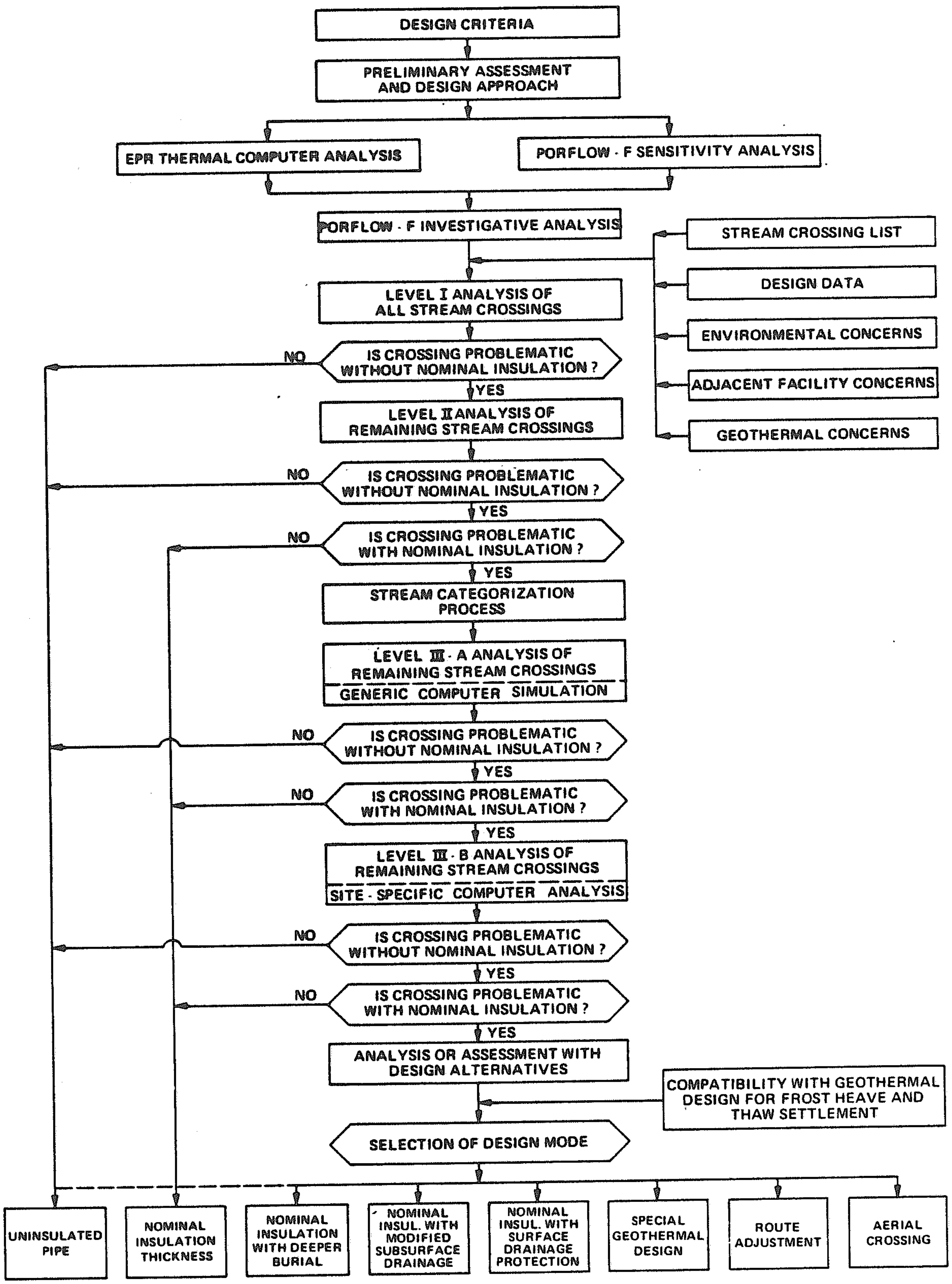
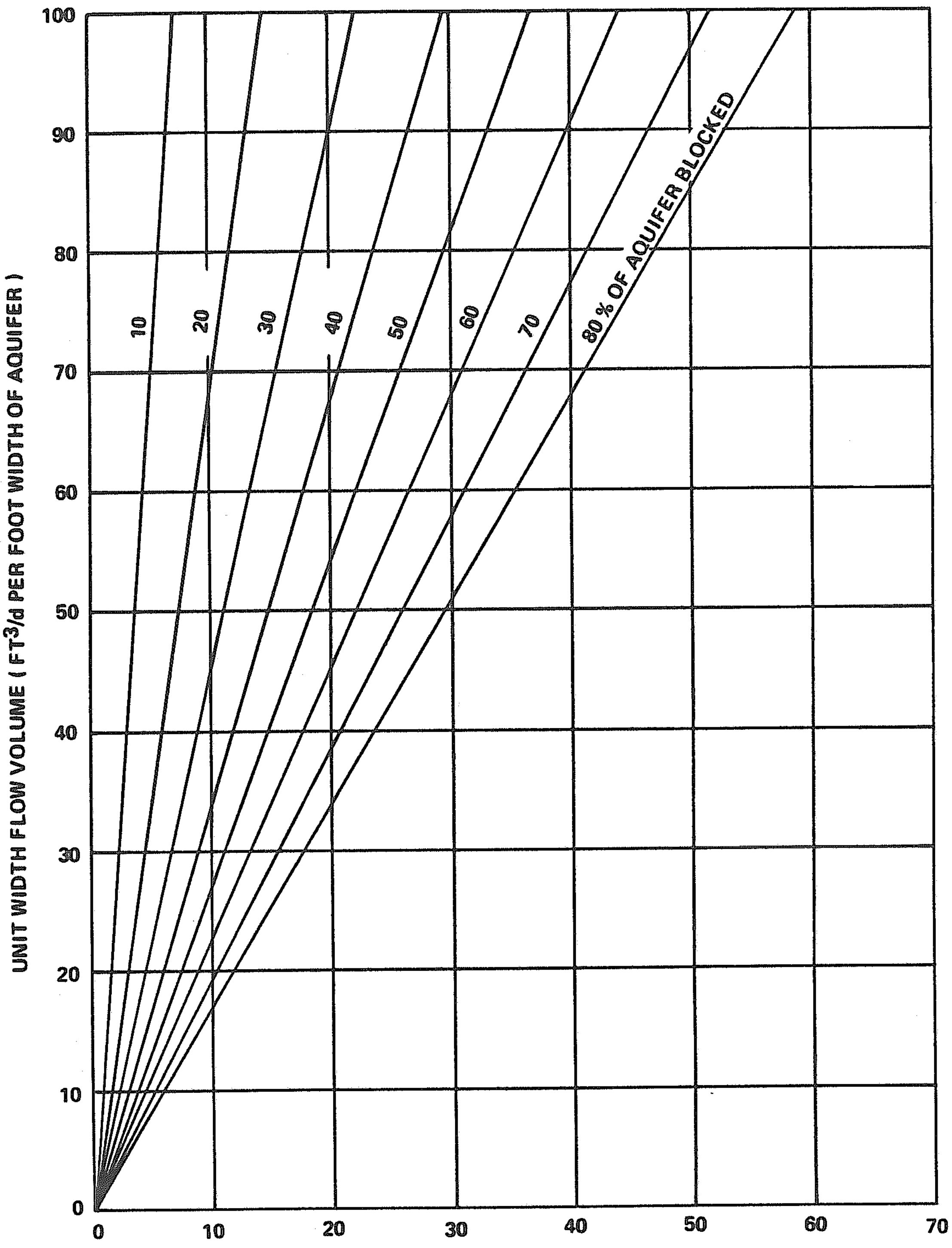


FIGURE 5 - 1

DESIGN CHART USED FOR COMPUTING POTENTIAL GROUND-WATER FLOW TO THE SURFACE RESULTING FROM CHILLED PIPE EFFECTS



NOTE : VALUES WERE PRODUCED USING PORFLOW - F.

FIGURE 5 - 2

WATER TABLE PROFILES ON SLOPING BARRIERS FOR $0.05 \leq \frac{I}{KS_b^2} \leq 0.25$

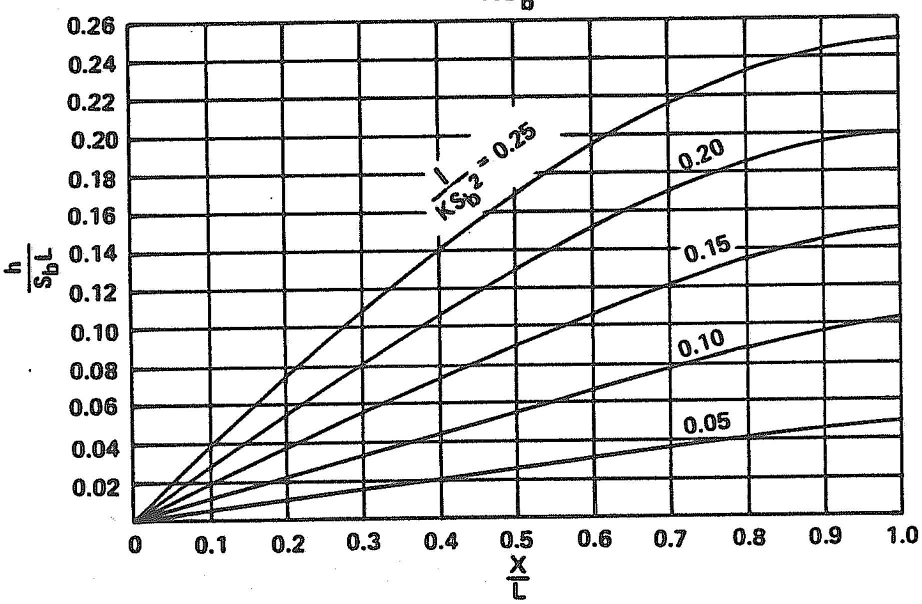


FIGURE 5 - 3A

WATER TABLE PROFILES ON SLOPING BARRIERS FOR $0.25 \leq \frac{I}{KS_b2} \leq 1.25$

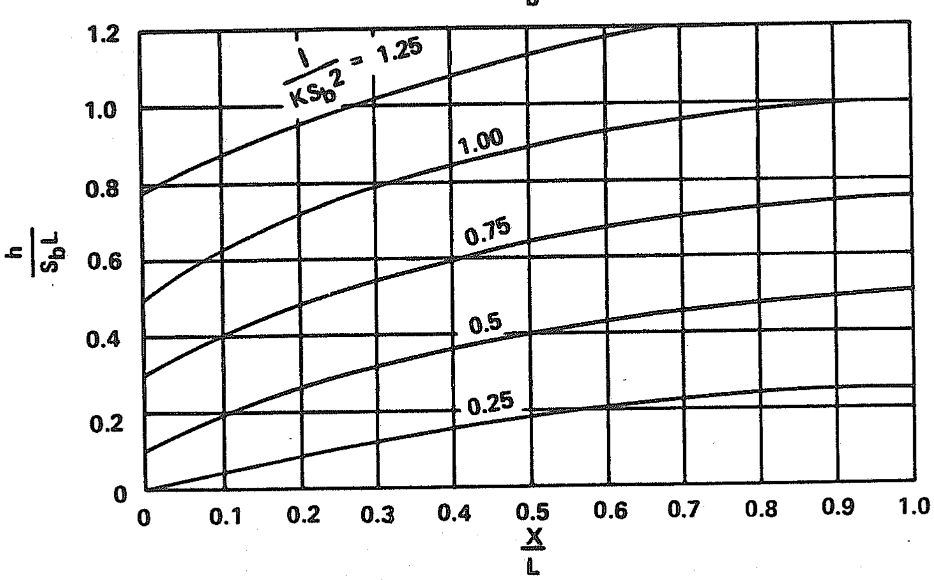


FIGURE 5 - 3B

CROSS - SECTIONAL PROFILE USED FOR COMPUTING STEADY - STATE WATER TABLE LOCATION

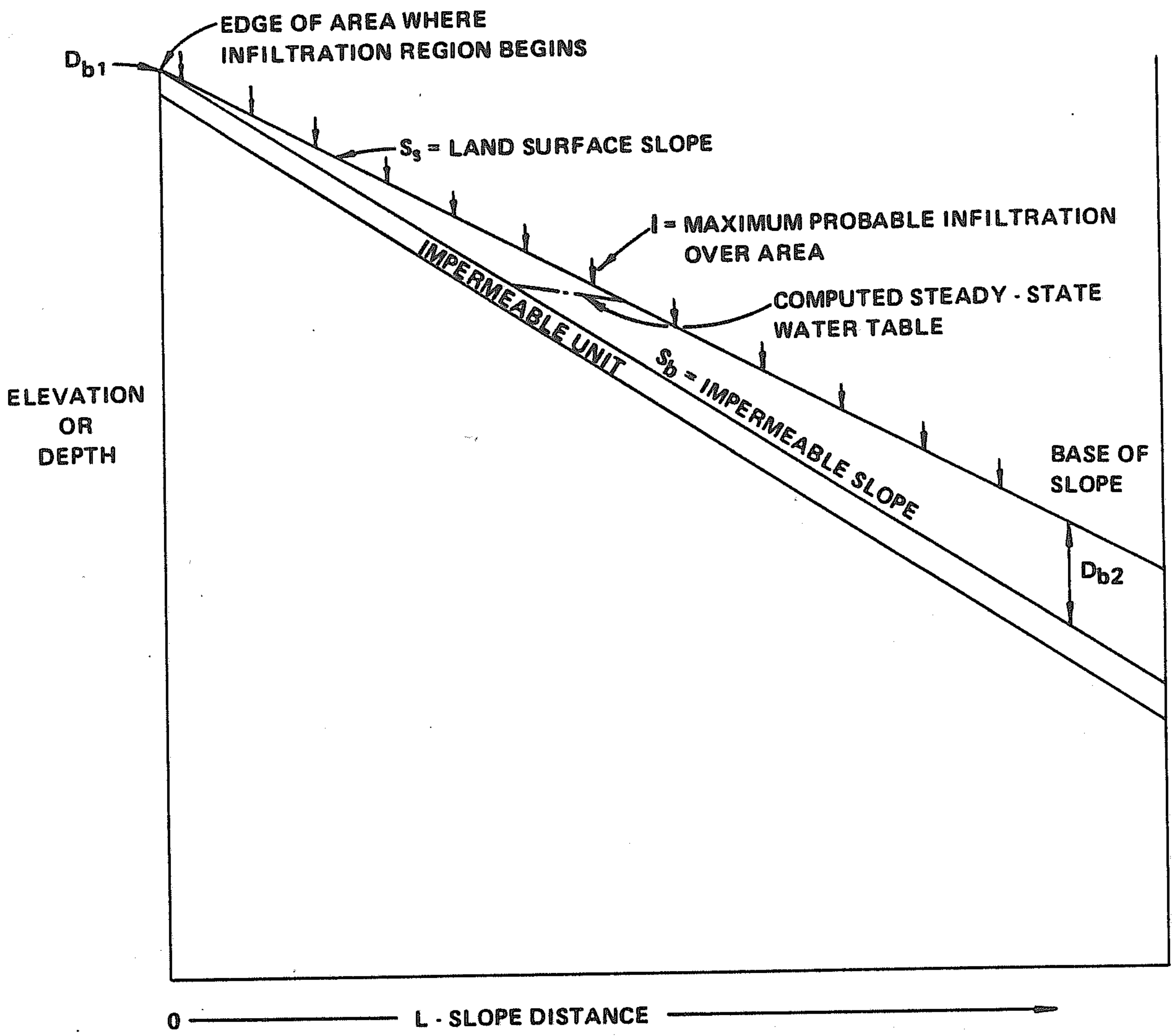
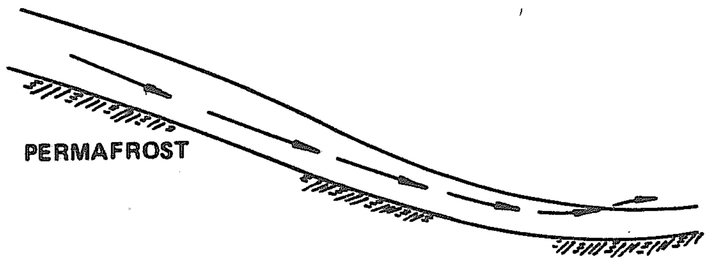
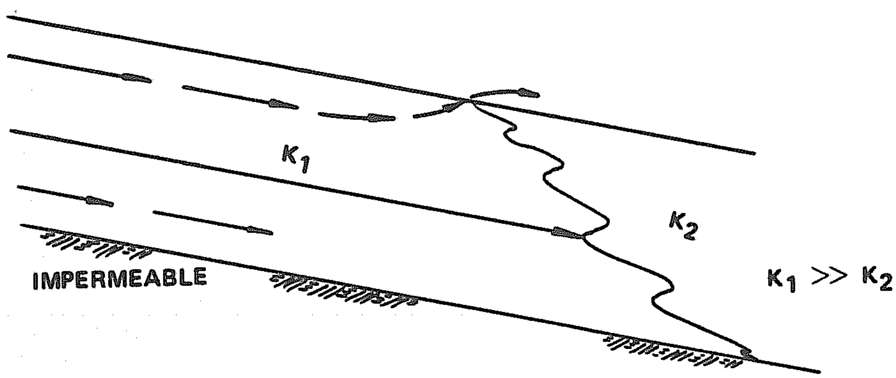


FIGURE 5 - 4

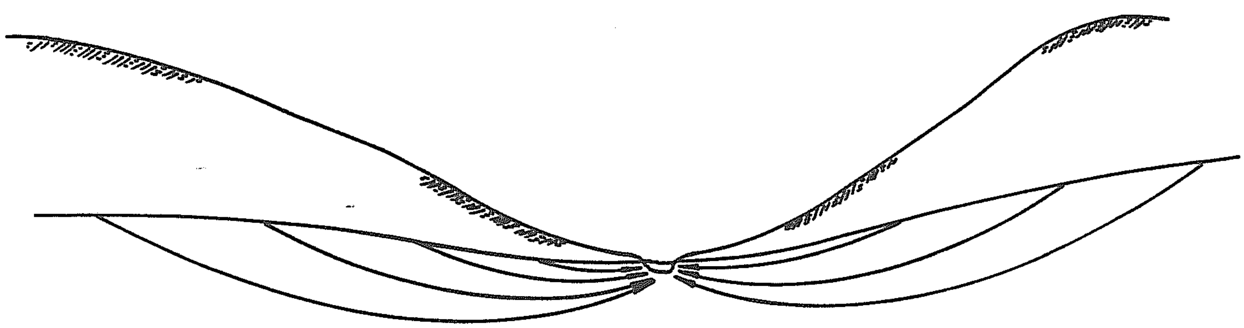
EXAMPLES OF NATURALLY OCCURRING GROUNDWATER DISCHARGE IN ARCTIC AND SUBARCTIC REGIONS OF ALASKA



ABRUPT CHANGE IN HYDRAULIC GRADIENT DUE TO CHANGE IN TOPOGRAPHY.



DISCHARGE DUE TO AN ABRUPT CHANGE IN HYDRAULIC CONDUCTIVITY.



GROUND - WATER DISCHARGE BY NATURAL GRAVITY FLOW OF GROUND - WATER.

FIGURE 5 - 5

GENERALIZED CROSS SECTION OF TYPE I FLOODPLAIN ALIGNMENTS

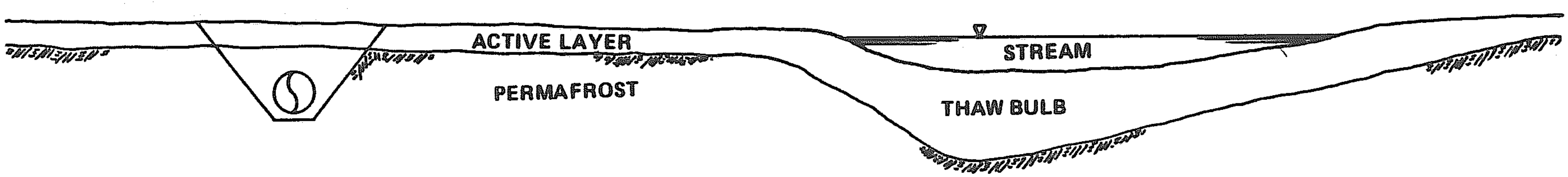
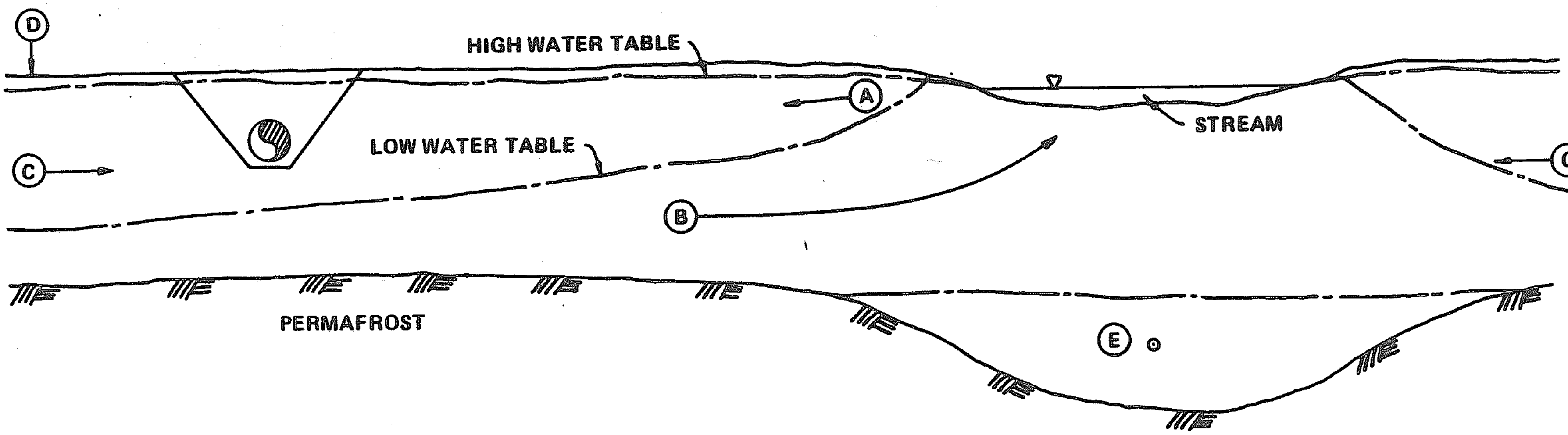


FIGURE 5 - 6

FIGURE 5 - 7

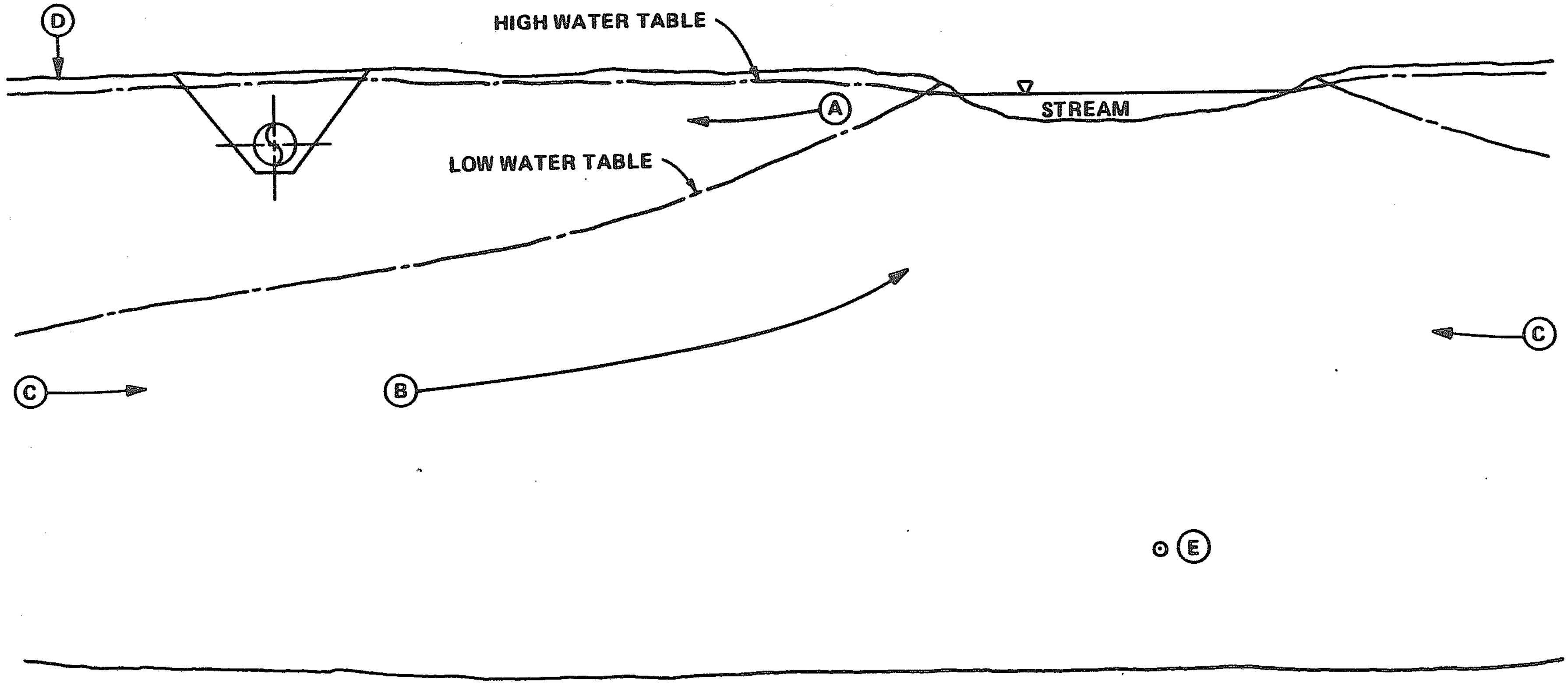
GENERALIZED CROSS SECTION OF TYPE II FLOODPLAIN ALIGNMENTS



(A) GROUND - WATER FLOW DIRECTION DURING HIGH STREAM FLOWS – INFLUENT CONDITIONS
(B) GROUND - WATER FLOW DIRECTION DURING LOW STREAM FLOW – EFFLUENT CONDITIONS
(C) GROUND - WATER FLOW CONTRIBUTIONS FROM LOCAL FLOW SYSTEMS INCLUDING ALLUVIAL FANS, SIDE SLOPES AND OTHER ADJACENT SOURCES
(D) INFILTRATION FROM PRECIPITATION AND SNOW MELT
(E) GROUND - WATER FLOW MOVES DOWN VALLEY DURING DRY STREAM PERIODS

FIGURE 5 - 8

GENERALIZED CROSS SECTION OF TYPE III FLOODPLAIN ALIGNMENTS



Ⓐ GROUND - WATER FLOW DIRECTION DURING HIGH STREAM FLOWS – INFLUENT CONDITIONS

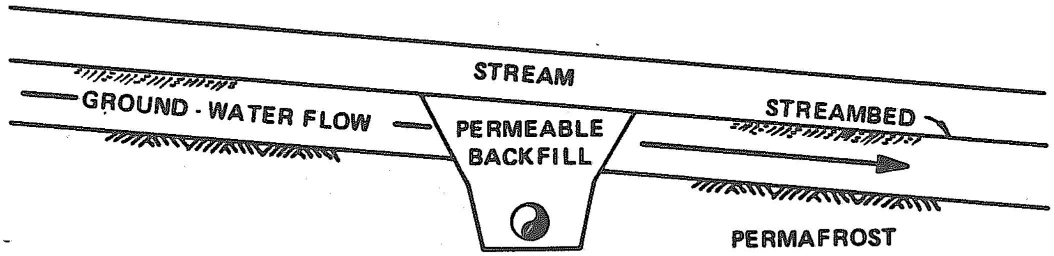
Ⓑ GROUND - WATER FLOW DIRECTION DURING LOW STREAM FLOW – EFFLUENT CONDITIONS

Ⓒ GROUND - WATER FLOW CONTRIBUTIONS FROM LOCAL FLOW SYSTEMS INCLUDING ALLUVIAL FANS, SIDE SLOPES AND OTHER ADJACENT SOURCES

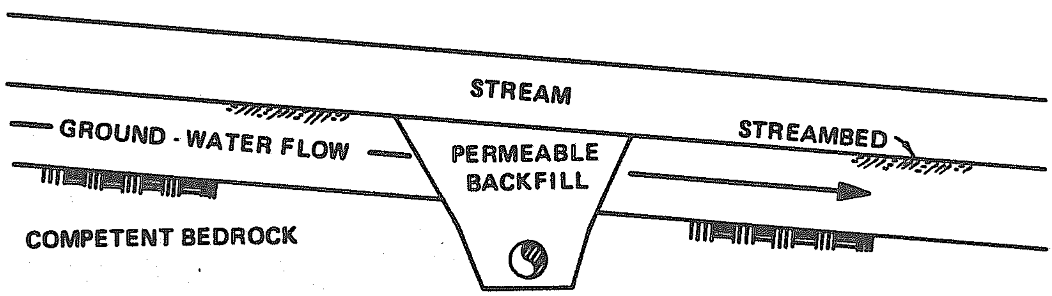
Ⓓ INFILTRATION FROM PRECIPITATION AND SNOW MELT

Ⓔ GROUND - WATER FLOW MOVES DOWN VALLEY DURING DRY STREAM PERIODS

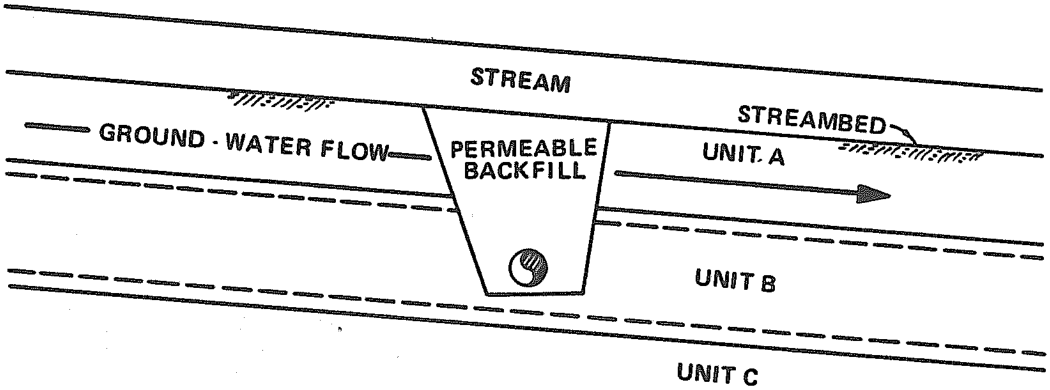
DEEPER BURIAL DESIGN SOLUTIONS FOR MOVING PIPELINE OUT OF PRIMARY GROUND - WATER FLOW FIELDS



PIPE LOCATED DEEPER INTO PERMAFROST AND OUT OF THE GROUND - WATER FLOW FIELD. FREEZE BULB HEIGHT WILL NOT EXCEED HEIGHT OF PERMAFROST TABLE.



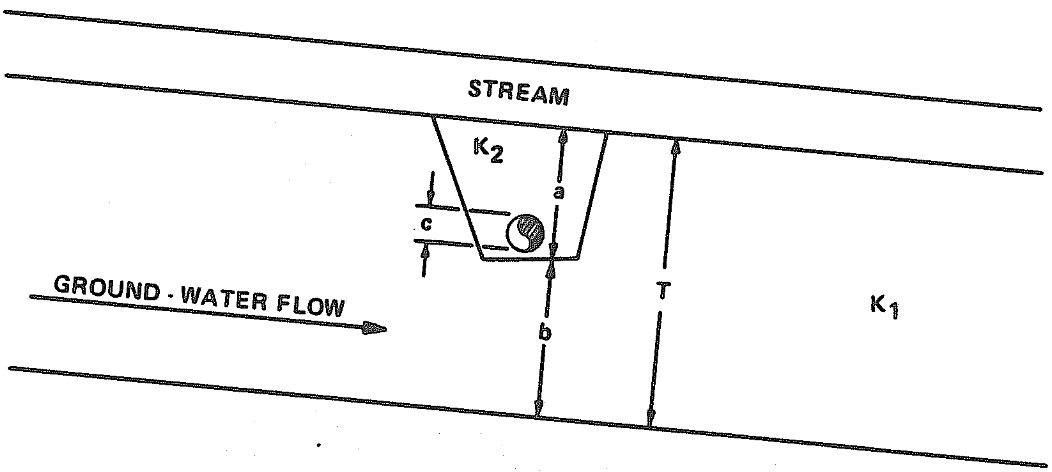
PIPE LOCATED DEEPER INTO COMPETENT BEDROCK AND OUT OF GROUND - WATER FLOW FIELD. FREEZE BULB HEIGHT WILL NOT EXCEED HEIGHT TO TOP OF COMPETENT BEDROCK.



PIPE LOCATED DEEPER INTO UNIT B WHICH HAS A LOWER HYDRAULIC CONDUCTIVITY VALUE THAN UNITS A AND C. FREEZE BULB WILL NOT EXCEED VERTICAL DIMENSIONS OF UNIT B.

FIGURE 5 - 9

DETERMINATION OF DITCH BACKFILL MATERIAL HYDRAULIC CONDUCTIVITY



THE TRANSMISSIVITY ACROSS THE DITCH ZONE CAN BE MAINTAINED EQUAL TO THAT UPSTREAM AND DOWNSTREAM IF:

$$aK_1 = (a - c)\,K_2$$

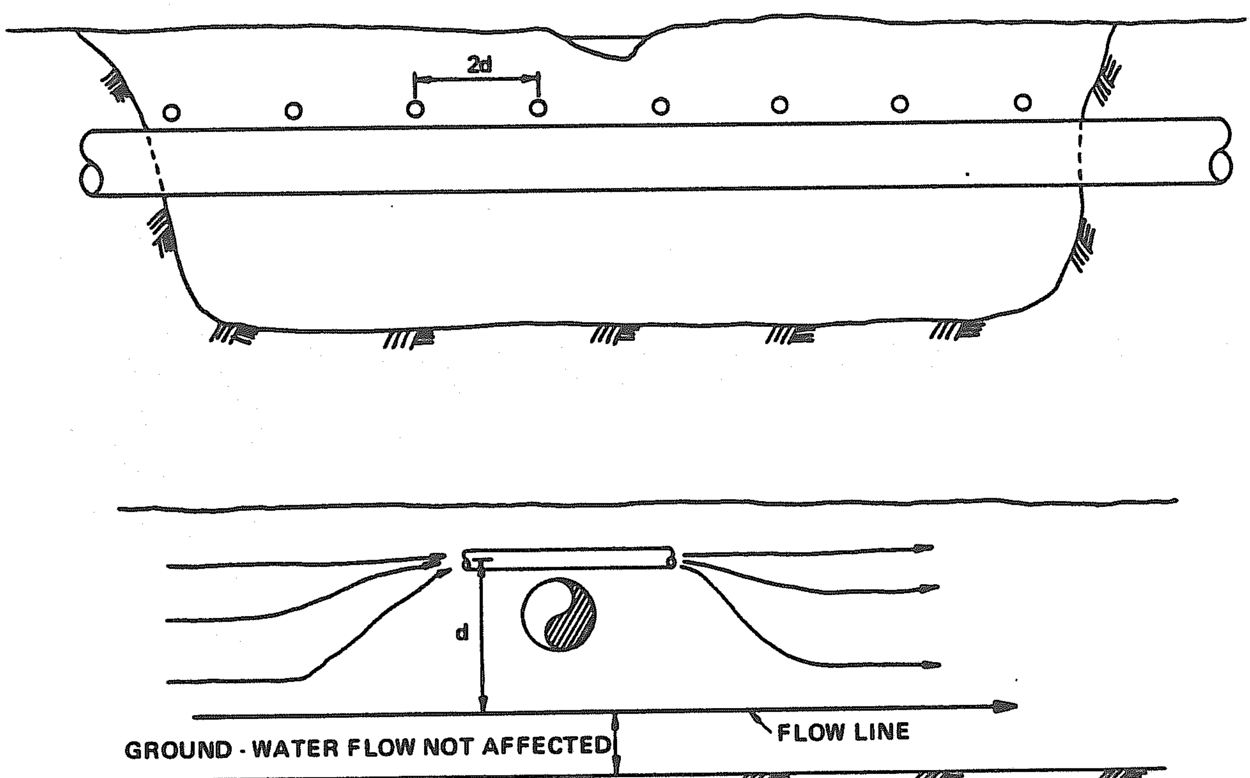
SUCH THAT $K_2 = \dfrac{K_1\,a}{(a - c)}$

WHERE K_1 IS THE HYDRAULIC CONDUCTIVITY OF THE NATIVE POROUS MEDIA, AND

K_2 IS THE HYDRAULIC CONDUCTIVITY OF THE DITCH BACKFILL MATERIAL.

FIGURE 5 - 10

INSTALLATION OF SUBSURFACE PIPE DRAINS FOR ACCOMMODATING GROUND - WATER FLOW AROUND THE CHILLED PIPELINE



d = RADIUS OF INFLUENCE OF PIPE DRAIN

FIGURE 5 - 11

8.0 REFERENCES

1. Wheeler, J.A. and T.W. Miller. General Purpose Permafrost Program - Version 10, Program Description, Exxon Production Research Company, 1980.

2. ANNGTC Project Report. "Comparison of PORFLOW-F and EPR Simulation Results." November, 1981.

3. Analytic and Computational Research, Inc. PORFLOW-F: A Mathematical Model for Groundwater Flow with Heat Transfer, Freezing, Thawing, and Atmospheric Heat Exchange - Volume I, Theory. Prepared for Northern Technical Services, Contract 4780-9-K086.1, September, 1981.

4. Analytic and Computational Research, Inc. PORFLOW-F: A Mathematical Model for Groundwater Flow with Heat Transfer, Freezing, Thawing, and Atmospheric Heat Exchange - Volume II, Users Manual. Prepared for Northern Technical Services, Contract 4780-9-K086.1, September, 1981.

5. ANNGTC Project Report. "PORFLOW-F Sensitivity Analysis." Unpublished Report, 1982.

6. Cederstrom, D.J., P.M. Johnson, and S. Subitzky. "Occurrence and Development of Groundwater in Permafrost Regions." U.S. Geol. Survey Circ. 275, 1953.

7. ANNGTC Project Report. "Groundwater Analysis Design Considerations, Stream Crossings for the Alaska Segment of the Alaska Natural Gas Transportation System," March, 1981. (CEDAT No. 4680-9-K086-80-0).

8. Freeze, R.A. and J.A. Cherry. Groundwater. Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1979.

9. U.S. Bureau of Reclamation. Drainage Manual. U.S. Department of the Interior, 1978.

10. Kane, D.L. "Physical Mechanics of Aufeis Growth," Institute of Water Resources, University of Alaska, Fairbanks, February, 1981.

APP A

NORTHWEST ALASKAN PIPELINE COMPANY
3333 Michelson Dr.
Irvine, California 92730
(714) 975-6007

503.0

GOA-82-2226

December 30, 1982

"BUSINESS" Information for Federal Government purposes in accordance with 10 CFR 1504 (F.R. Vol. 46, No. 240, December 15, 1981, pages 61222 thru 61234).

Mr. W. T. Black
Director, Office of Engineering
Office of the Federal Inspector
2222 Martin
Irvine, CA 92715

Subject: Transmittal of Chilled Pipe Effects

Dear Mr. Black:

Enclosed is the following confidential/proprietary document, identified in our "Key Activity Checklist; Revision No. 3," dated November 30, 1982, as Item No. 54:

Chilled Pipe Effects on Streams, December 30, 1982, Rev. 2

The enclosed information is considered confidential/proprietary by Northwest Alaskan Pipeline Company and remains the property of Alaskan Northwest Natural Gas Transportation Company, a partnership. The petition attached to this letter requests OFI to consider this material "BUSINESS" information pursuant to 10CFR Part 1504. All rights are reserved to the enclosed work, and unauthorized reproduction is prohibited. This material is protected as an unpublished work under the Copyright Law of the United States, 17 USC §101 et seq.

Very truly yours,

NORTHWEST ALASKAN PIPELINE COMPANY

George P. Wuerch
Manager, Regulatory
and Governmental Affairs

GPW/wpc
Enclosures (4 copies)

cc: N. Hengerer, OFI, Washington, D.C. (w/enclosure)
A. G. Ott, SPO, Fairbanks (w/2 copies of enclosure)
J. F. McPhail, Alyeska, Houston (w/1 copie of enclosure)
F. R. Fisher, Alyeska, Anchorage (w/2 copies of enclosure)

Enclosure to Northwest Alaskan Pipeline Company
Letter GOA-82-2226 of December 30, 1982 to
Mr. W. T. Black

PETITION FOR "BUSINESS" DESIGNATION
SUBMITTED TO OFI PURSUANT TO 10 CFR PART 1504

I. The information contained in the above referenced Northwest Alaskan Pipeline Company (NWA) letter, qualifies for a "BUSINESS" designation on the basis that it is confidential/proprietary, commercial information, the release of which may substantially impair the competitive position of the sponsors of the Alaska segment of the Alaska Natural Gas Transportation System (ANGTS). NWA has incurred substantial costs to develop the information, involving major expenditures, including both direct and indirect costs. Moreover, the sponsors do not have a final, unconditional Certificate of Public Convenience and Necessity from the Federal Energy Regulatory Commission (FERC), and the information clearly would be of substantial value to anyone contemplating the construction in Alaska or in similar climates and geologic regimes. Even after a final FERC certificate has been obtained, the information contained in the document submitted is of such a nature that it might be used in third-party litigation against the sponsors. NWA has given serious consideration to a request for a "SENSITIVE" designation and to the recent order from the International Trade Commission, Department of Commerce (e.g., 15 CFR Parts 379, 385 and 399, published F.R. Vol. 47, No. 2, January 15, 1982, p. 141) restricting export of technical data related to gas transmission. Although the less restrictive "BUSINESS" designation has been requested, the technology represented by this information clearly should not be disclosed except as authorized by NWA.

II. The OFI may contact the following named persons concerning this petition:

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	JEMyrick	(w/enclosure)
	WJWatts	(w/enclosure)
	MJSotak	(w/enclosure)
	EAKuhn	(w/enclosure)
	RMIsaacs	(w/enclosure)
	DCM Binder	(w/o enclosure)
	File	(w/enclosure)
	RDM	
	Project Advisors	(w/enclosures)