GEOLOGICAL SURVEY OF CANADA

OPEN FILE 2226

REPORT OF GEOTHERMAL MODELLING, OFFSHORE TEMPERATURE PROFILES AT ANGASAK AND AMAULIGAK, BEAUFORT SHELF

GEO-ENGINEERING (M.S.T.) LTD.

1990

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Title page

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ACKNOWLEDGEMENTS

We would like to thank Dr. J.F. Nixon for his assistance and expertise in saline permafrost soils which plays such a key aspect of geothermal modelling of offshore permafrost.

1.0 INTRODUCTION

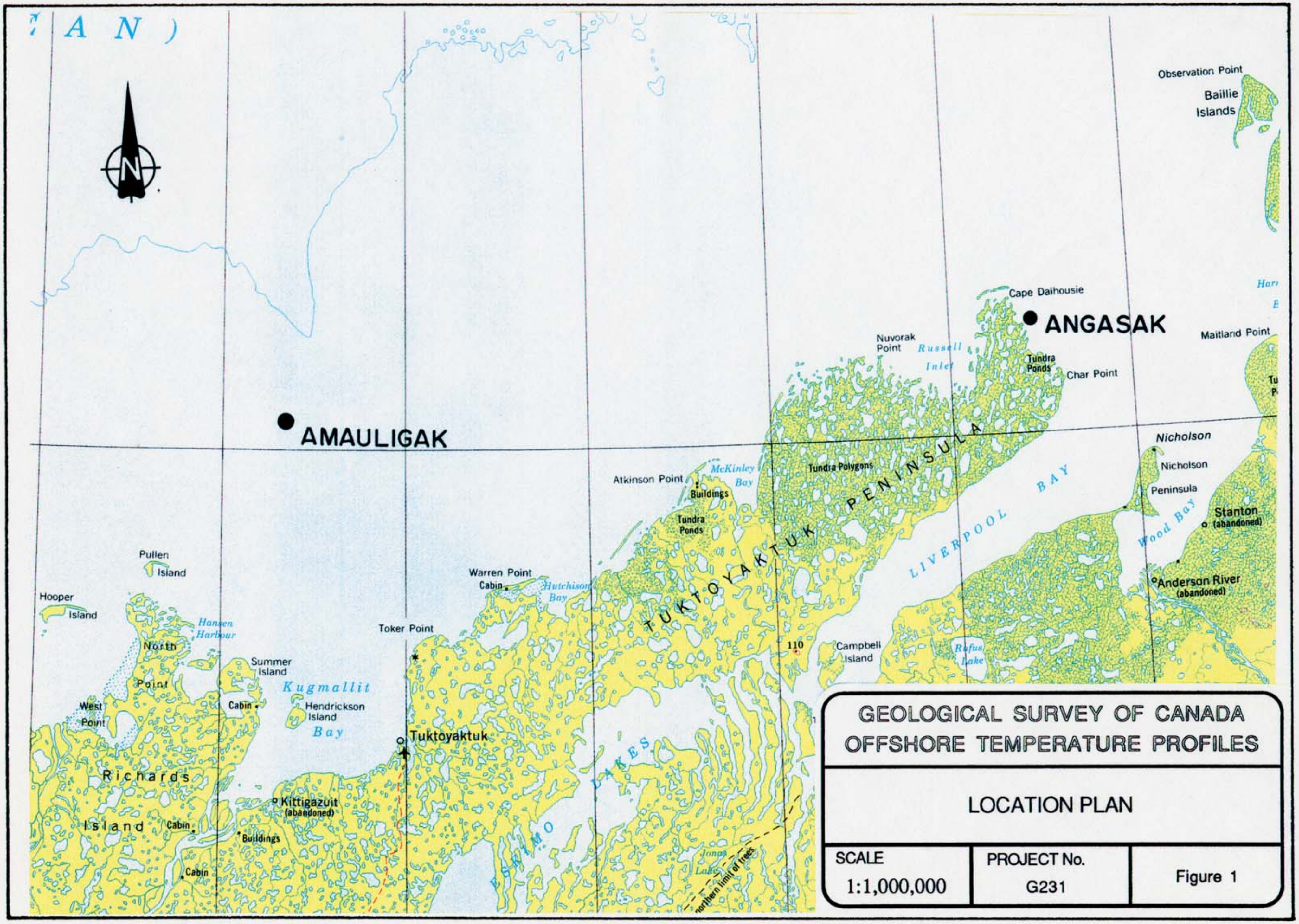
Oil and gas exploration in the Beaufort Sea has recently led to the recovery of geological and geotechnical information previously unavailable. One area of particular interest to geologists has been related to offshore permafrost. It has been speculated by many that geothermal modelling of present day temperature profiles in offshore permafrost could lead to other means of simulating geological history. An event of relatively recent geological history involving offshore permafrost in the Beaufort area is marine transgression. It has been well documented that much of the Beaufort Shelf was above the ocean and formed in a non-marine environment. It is only in relatively recent geological times that these areas have been inundated by the Beaufort Sea. Mean surface temperatures before submergence have been estimated to be cold (i.e. -8 to -16°C) which resulted in the aggradation of permafrost. With the subsequent submergence of these regions under water at temperatures very near or above the freezing point of the soil, the permafrost is no longer in equilibrium and is, therefore, considered relict and is likely degrading.

The scope of work of this study was to model this recent marine transgression and produce two benchmark runs matching measured temperature profiles at two wellsites; Angasak and Amauligak located off the coast line of Tuktoyaktuk Peninsula as shown in Figure 1. The results of this modelling and a brief overview of the problem layout are discussed in the following sections.

2.0 PROBLEM OUTLINE

The presence of deep permafrost below the Beaufort Shelf can only be explained by past exposure to very cold mean ground surface temperatures for a very long time prior to submergence by the Beaufort Sea. The work by Hill et al (1985) has produced a relative sea level curve with time based on radio carbon dating which is shown in Figure 2. Organics and peat which were deposited in a freshwater marshy environment were identified in numerous boreholes in their study and are considered a fairly reliable indication of the time of submergence.

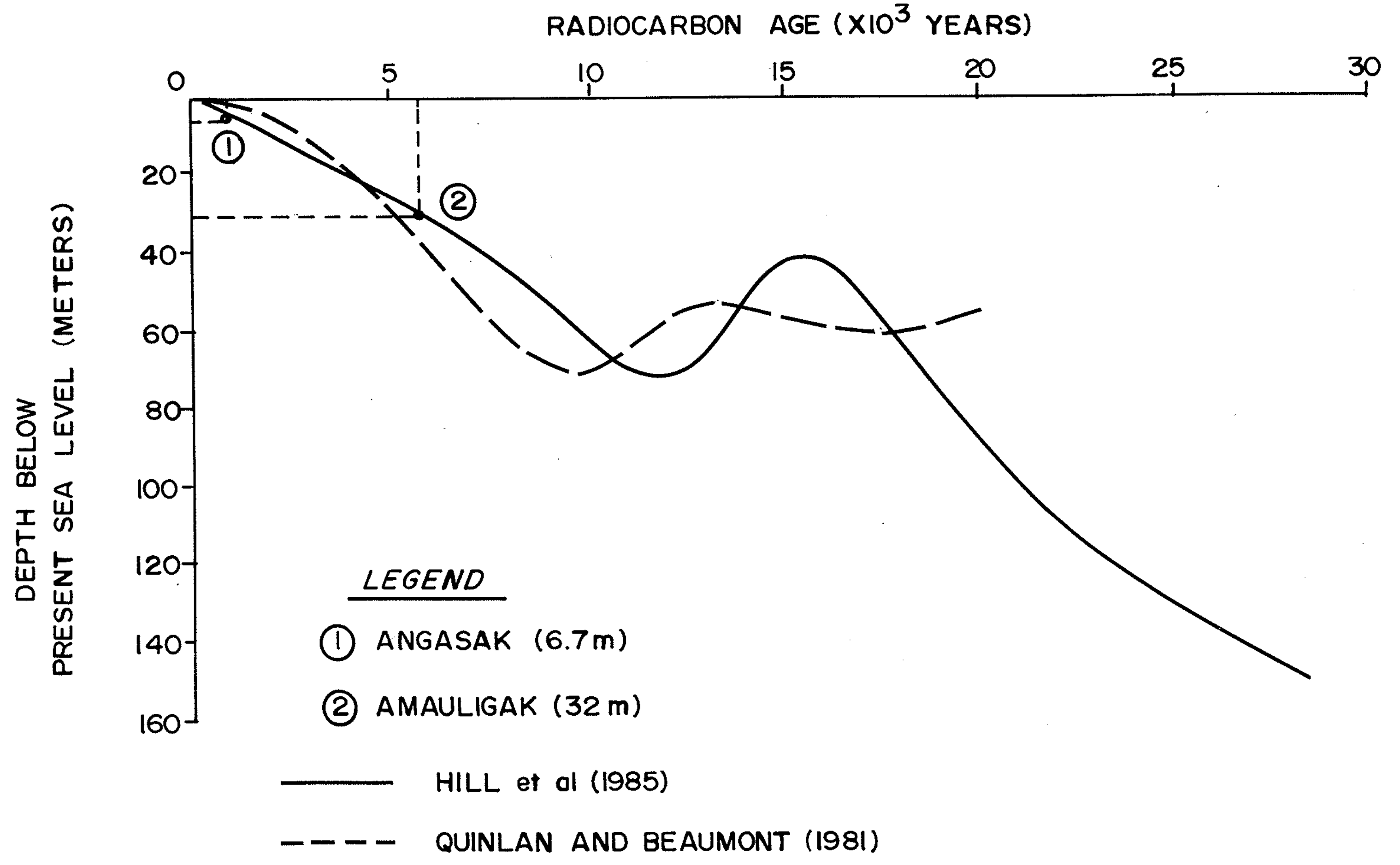
Present theory suggests the offshore permafrost regions were exposed to cold surface temperatures for a relatively short duration (i.e. 13,000 to 15,000 years). The work by Nixon (1986), however, suggests that the time required to create the great thickness of



GEOLOGICAL SURVEY OF CANADA
OFFSHORE TEMPERATURE PROFILES

LOCATION PLAN

SCALE	PROJECT No.	
1:1,000,000	G231	Figure 1



N.B. CURVE TAKEN FROM CJES v. 22, 1985

GEOLOGICAL SURVEY OF CANADA
OFFSHORE TEMPERATURE PROFILES

RELATIVE SEA LEVEL CURVE
BEAUFORT SHELF

SCALE	PROJECT No.	
As shown	G231	Figure 2

permafrost observed offshore cannot be properly explained by this theory and much longer periods of exposure to cold temperatures were likely required.

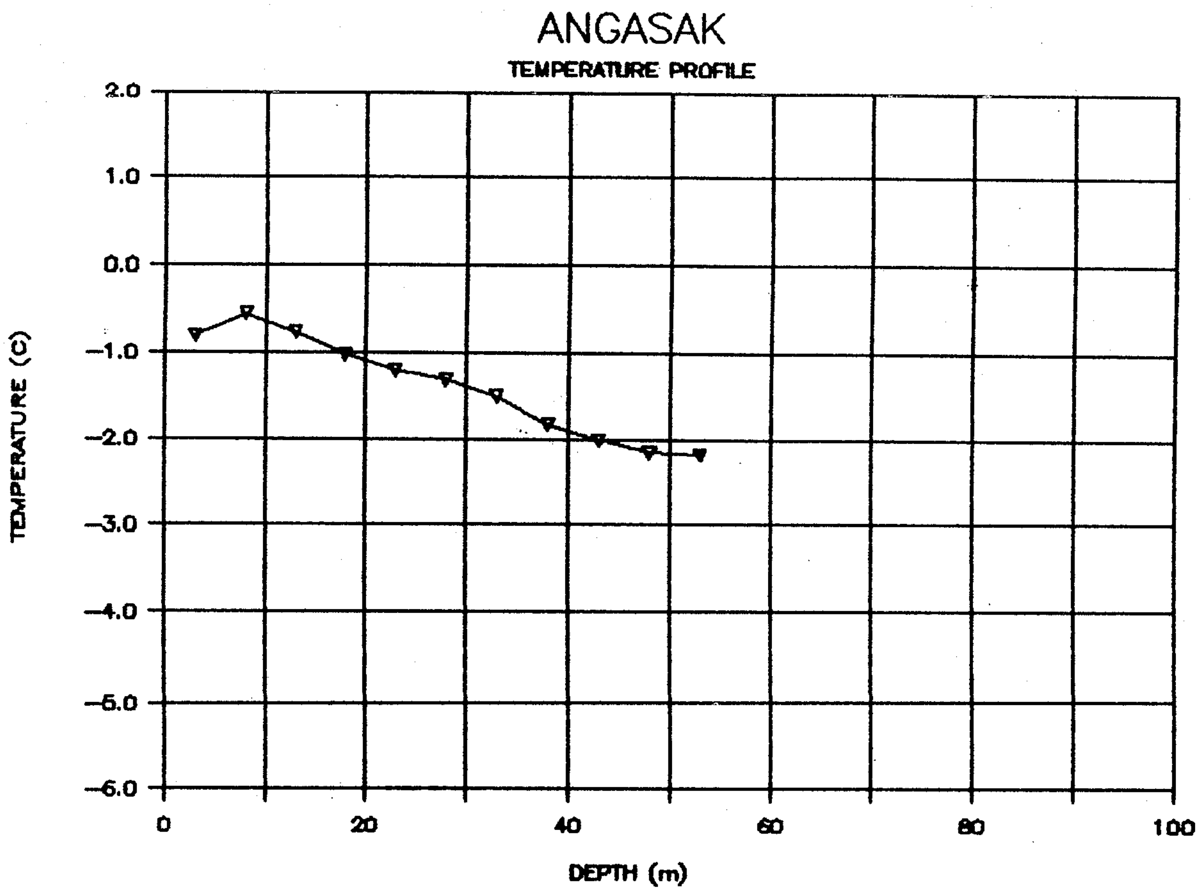
For the purposes of our study, we have assumed initial mean surface temperatures of between -8 and -16°C existed for a long enough time to produce ground temperatures which were linear with depth to the base of permafrost, varying from 400 to 700 m. Initial boundary temperatures suggested in the service contract were -12°C for the Angasak site and -14°C for the Amauligak site. No attempts were made to accurately model aggradation or growth of the permafrost zone in this study.

3.0 TEMPERATURE PROFILES

3.1 ANGASAK TEMPERATURE PROFILE

The temperature profile provided for the first benchmark run was for the Angasak wellsite and is shown plotted in Figure 3. The thermistor string was installed in a 56 m geotechnical hole drilled from the sea ice. The depth of water was reported as being 6.7 m. Previous geothermal modelling undertaken by Taylor and Judge (1988) at the site, assumed sea bed temperatures ranged between 0 and -1°C. Readings from the thermistor bead at 2 m above the sea bed suggest that sea bed temperatures as low as -1.6°C are possible. However, these readings were only for a short period of time during the winter and may not reflect mean sea bed temperatures.

It is understood depth of permafrost in the area of Angasak ranges from 400 to 500 m (Judge et al, 1987). The thermistor string, therefore, only covers the top 15 percent of the permafrost layer. A match of the temperature profile in this top region could, therefore, theoretically be made that may not reflect conditions at depth. As a result, the accuracy of prediction of the time of marine transgression may be prone to more error than if a more complete temperature profile were available.



GEOLOGICAL SURVEY OF CANADA
OFFSHORE TEMPERATURE PROFILES

ACTUAL OFFSHORE TEMPERATURE PROFILE
ANGASAK

SCALE	PROJECT No.	
As shown	G231	Figure 3

3.2 AMAULIGAK TEMPERATURE PROFILE

The temperature profile provided for the second benchmark run was for the Amauligak wellsite and is shown plotted in Figure 4. Depth of water was reported as being 32 m. Details of the thermistor string installation can be found in the paper by Taylor et al (1989). The thermistor string at Amauligak is much deeper than at Angasak extending to a depth below sea level of 336.5 m.

Permafrost in the area of Amauligak is reported to be in the range of 600 and 700 m (Judge et al, 1987). Therefore, the temperature profile available for modelling permafrost at Amauligak is more complete than at Angasak, and covers roughly half the permafrost layer.

Comparing the temperature profiles for Amauligak and Angasak, it is likely the Angasak data reflects a relatively early stage of permafrost degradation and Amauligak is much more advanced. This is consistent with the relative sea level depth being much deeper at Amauligak than at Angasak. The Amauligak temperature profile has degraded to a state where it is almost isothermal with depth. This degraded condition for Amauligak is difficult to accurately model because the change in temperature profile shape with time becomes very slow at this late stage of degradation.

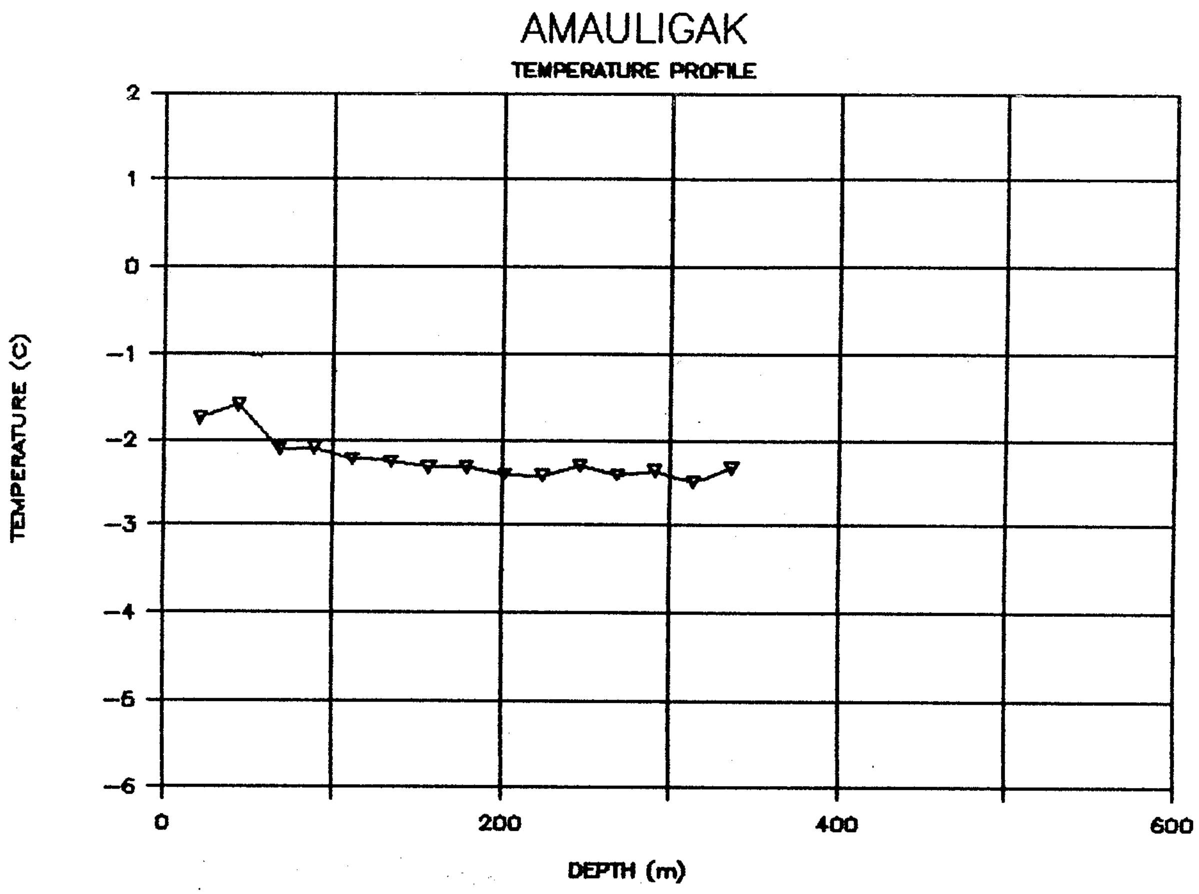
4.0 GEOTECHNICAL AND GEOTHERMAL DATA

4.1 ANGASAK DATA

Geotechnical and geothermal data were provided for the top 56 m of the soil profile for Angasak. The soil and permafrost stratigraphy is summarized in Table 1.

TABLE 1
Soil and Permafrost Stratigraphy - Angasak

Depth Range (m)	Soil Description	Permafrost Condition
0-29	Sand	No ice present
29-32	Sand	Ice-bonded or ice-rich
32-41	Silty clay	Ice-bonded or ice-rich
41-52	Fine sand	Ice-bonded or ice-rich
52-56	Silty clay to clayey silt	Ice-bonded or ice-rich



GEOLOGICAL SURVEY OF CANADA
OFFSHORE TEMPERATURE PROFILES

ACTUAL OFFSHORE TEMPERATURE PROFILE
AMAULIGAK

SCALE As shown	PROJECT No. G231	Figure 4

As can be seen, approximately 32 m of sand, unfrozen to 29 m, overlays interbedded sand, silts and clays to a depth of 56 m. Moisture content profiles and salinity profiles with depth are shown plotted in Figure Nos. 5 and 6, respectively. The salinity of the sand in the top 32 m of the soil profile is high (approximately 35 ppt) which results in a dramatically reduced freezing point. The work by Ono (1975) has shown the dramatic shift and effect of salinity on the unfrozen water content function. Salinity depresses the freezing point of soil or sea ice as shown in Figure 7. Therefore, soil with a salinity of 35 ppt has a freezing point of approximately -1.8°C.

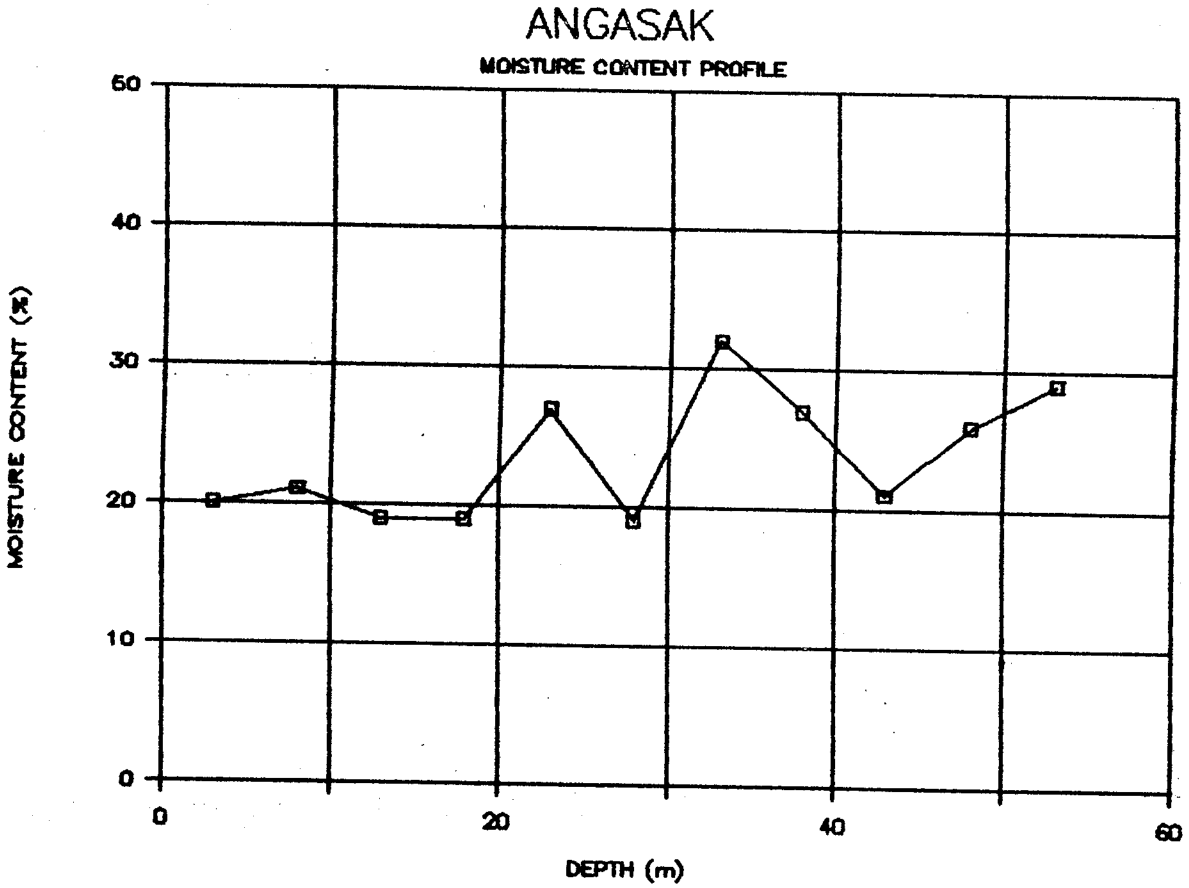
The amount of water which remains unfrozen for a given soil is best expressed by a function of temperature. Discrete temperature phase changes do not model freezing/thawing processes very well for most soils as discussed in the paper by Nixon (1986). An unfrozen water content function of the following form has been shown to model reasonably well the behavior of freezing/thawing soils.

$$W_u = (P + \exp(QT + R))/100$$

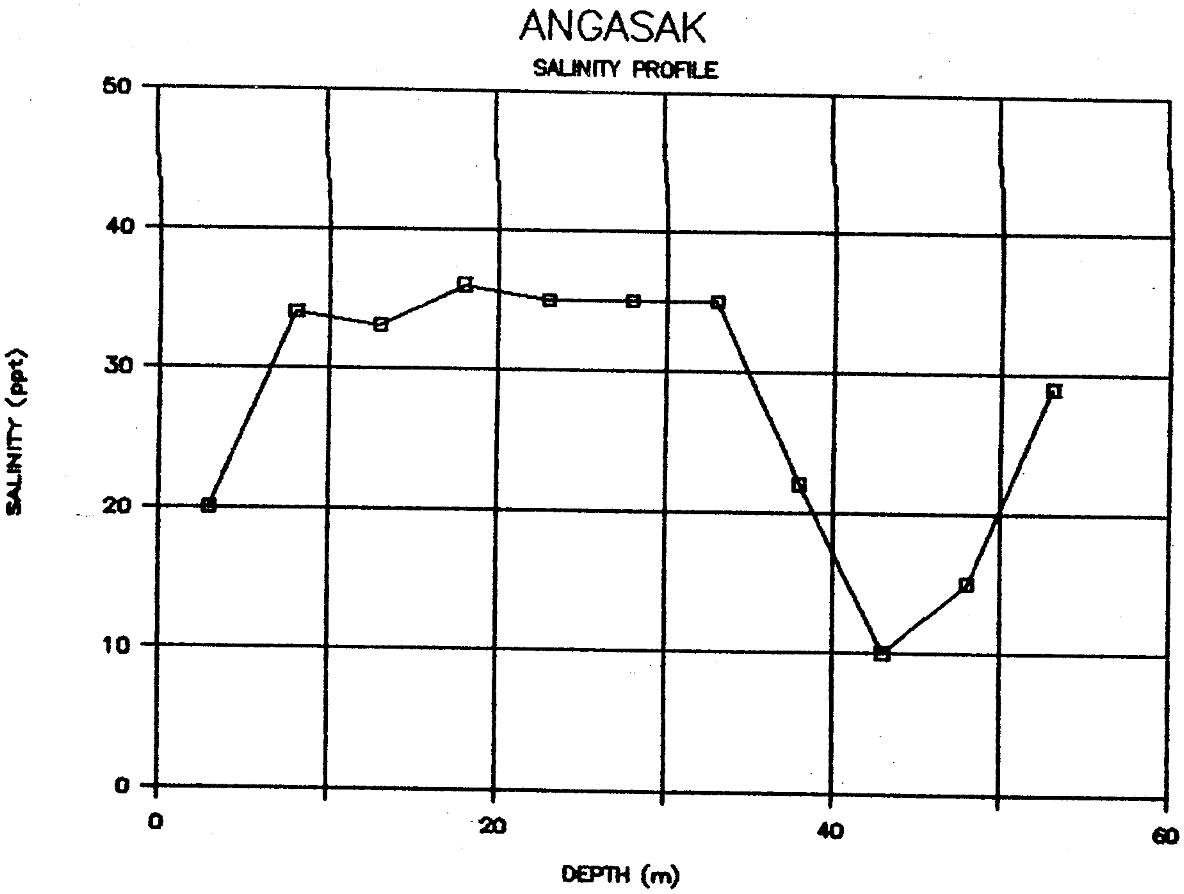
where: P and Q = constants that vary with soil type
R = ln (100 - P), giving the function, W_u, value of unity at 0°C
T = temperature (°C)

The first constant, P, is the percentage of the total water content that never freezes even at very low temperatures and may vary from zero for sands or gravels to as much as 25 percent for silty clay soils. The constant, Q, prescribes the rate at which the unfrozen water content decreases with negative temperature. The parameter can vary from 1-2 for silts and clays to as high as 20 for sands and gravels. The actual selection of these parameters is determined by experience, fitting the above function to published data for similar soils, or by laboratory testing (Anderson et al, 1973).

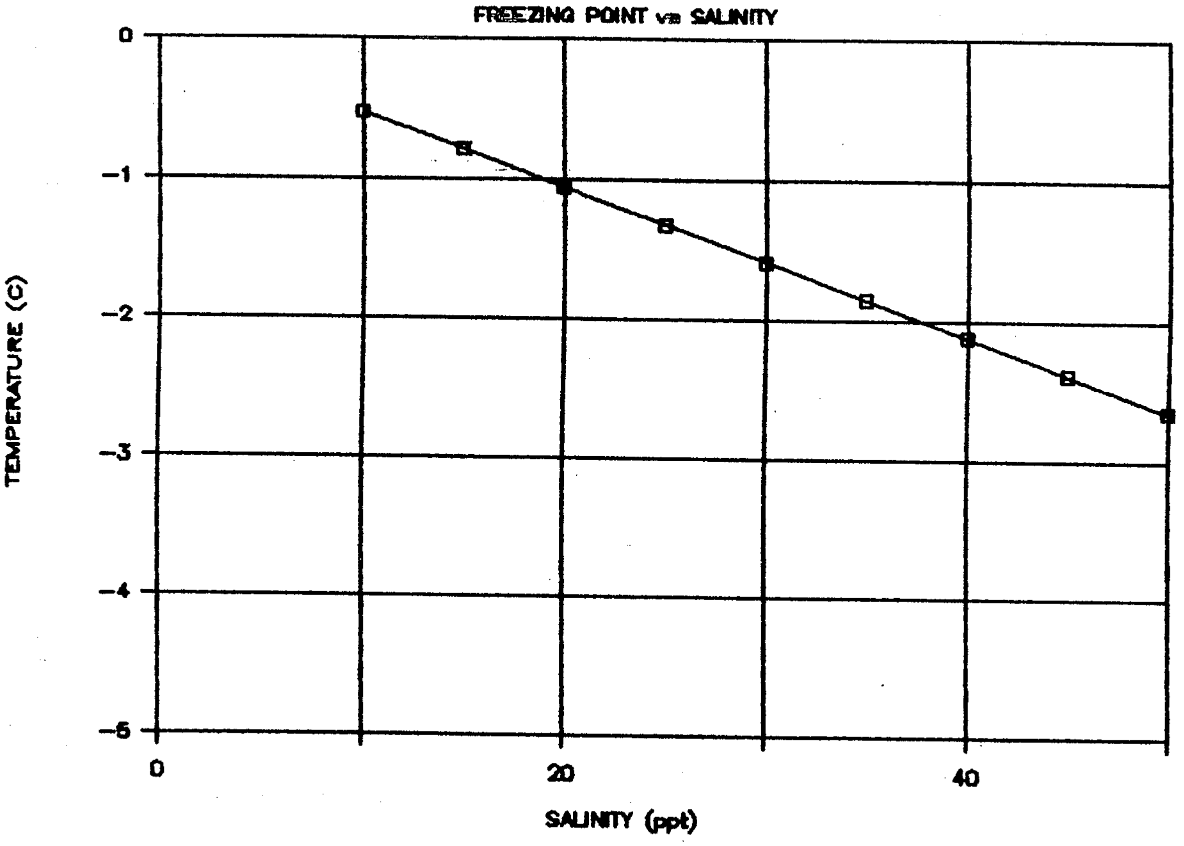
For saline soils, the unfrozen water content curve established by Ono (1975) appears to be a reasonable approximation. The parameters P and Q were adjusted until a match to the Ono function was achieved. A typical match is shown in Figure 8 for a sand of salinity 35 ppt found at Angasak.



GEOLOGICAL SURVEY OF CANADA OFFSHORE TEMPERATURE PROFILES		
MOISTURE CONTENT PROFILE ANGASAK		
SCALE As shown	PROJECT No. G231	Figure 5



GEOLOGICAL SURVEY OF CANADA OFFSHORE TEMPERATURE PROFILES		
SALINITY PROFILE - ANGASAK		
SCALE As shown	PROJECT No. G231	Figure 6

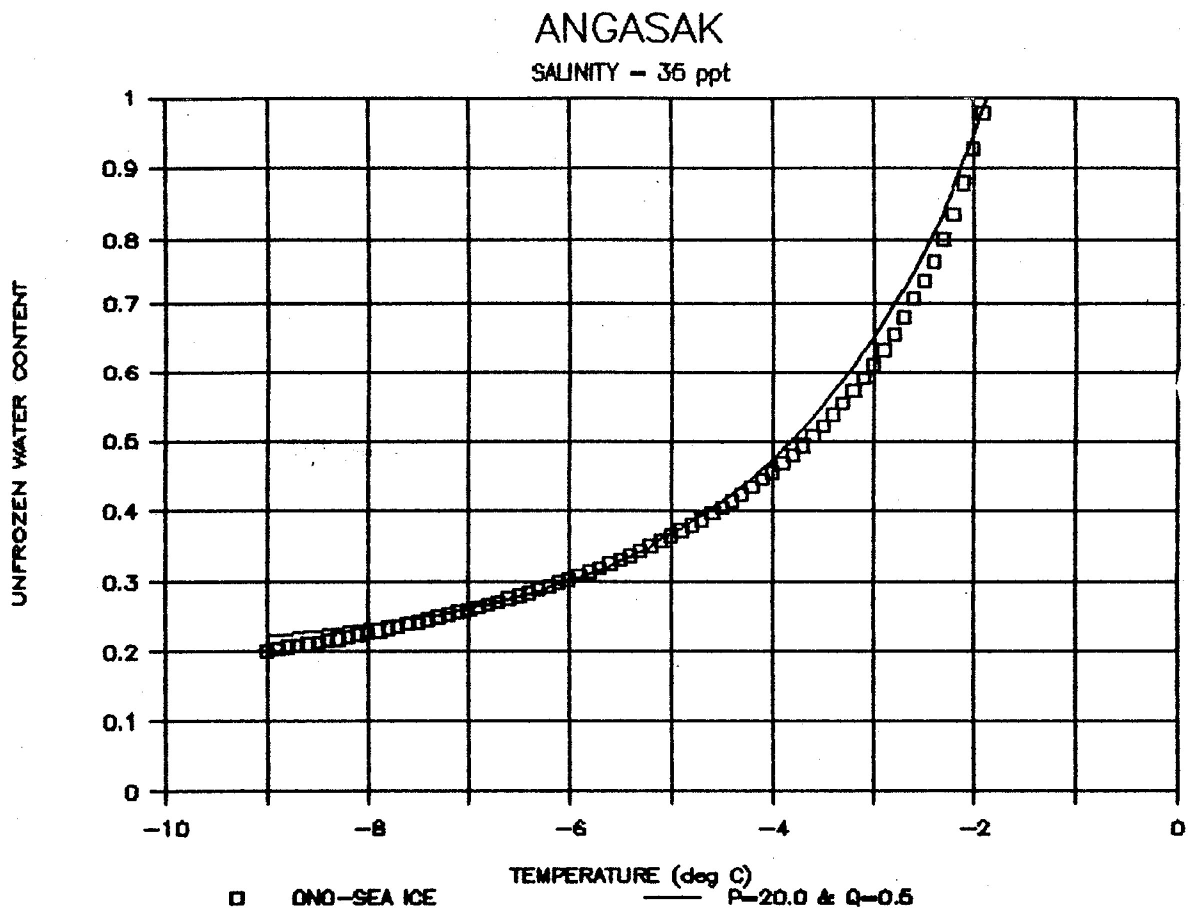


SOURCE: ONO (1975)

GEOLOGICAL SURVEY OF CANADA
OFFSHORE TEMPERATURE PROFILES

EFFECT OF SALINITY ON
FREEZING POINT

SCALE	PROJECT No.	
As shown	G231	Figure 7



SOURCE: ONO (1975)

GEOLOGICAL SURVEY OF CANADA
OFFSHORE TEMPERATURE PROFILES

TYPICAL UNFROZEN WATER CONTENT
CURVE - 35 ppt SALINITY

SCALE	PROJECT No.	
As shown	G231	Figure 8

The moisture content data varied between 19 and 32 percent by dry weight with the average being around 24 percent. Due to many variations in the moisture content with depth, but over a reasonably narrow range of values, the average moisture content value was assumed for all modelling. Dry densities were computed automatically by the model assuming saturation and a specific gravity of 2.67.

Thermal conductivities were provided for the soil profile at Angasak and are summarized in Table 2.

TABLE 2

Thermal Conductivities - Angasak

Depth (m)	Soil Description	Thermal Conductivity (Estimate) (W/mK)
0-32	Sand	4.0
32-41	Silty clay	1.8
41-52	Fine sand	2.5
52-56	Silty clay to clayey silt	1.8

These values were used as provided where possible, and averaged in cases where soil stratigraphy consisted of very thin layers in relation to the overall permafrost profile. Actual values used are summarized for each run in the section on the computer modelling.

As geotechnical and geothermal data was only available for the top 56 m, extrapolation of average soil conditions over the full depth of the model had to be made. Details of the profiles used for modelling are discussed in the section on the computer modelling.

4.2 AMAULIGAK DATA

The geotechnical and permafrost information collected for Amauligak is proprietary for the present, and is unavailable for this current study. Typical values of soil properties and salinities were assumed within bounds suggested in the information provided with the service contract and based on Angasak data. Where possible, attempts were made to bound the likely ranges of parameters, particularly salinity.

Thermal conductivity was assumed to be 2.5 W/mK for the entire soil profile as suggested in the service contract.

Details of the input parameters used for modelling are summarized for each run in the section on computer modelling.

5.0 METHODOLOGY

The geothermal model used for all analyses in this study was the one-dimensional finite difference program THERM1 under licence from Dr. J.F. Nixon. Details of the full capabilities and input parameters of the model can be found in the User's Manual enclosed as Appendix A.

Initial ground temperature conditions assumed a surface temperature between -8 and -18°C varying linearly with depth to the base of the permafrost. This condition was assumed to represent the geothermal situation immediately prior to inundation. Submergence under the Beaufort Sea was then taken into account by applying a surface temperature directly to the top soil layer varying from -1.5 to +0.5°C to represent ranges of sea bed temperature which likely existed. Several large elements below the base of permafrost were imposed on the soil profile to correctly model the degradation of the base of the permafrost from the geothermal gradient.

Suggested thermal conductivities and other geotechnical information as discussed in the previous section were utilized where possible. In some cases, the soil layers were too small to be precisely in the model due to the small time steps that would have resulted, and some approximation to stratigraphy had to be made.

Unfrozen water content functions were fitted for various salinities and used in the model. The depression of the freezing point by salinity was also taken into account by the model so phase changes could occur in different layers at different temperatures.

A given set of input parameters was then run until either a match of the actual temperature profile occurred, or it became obvious no match was possible. The criteria for a match was not based on a least squares fit, but rather on the general shape of the profile and correct modelling of phase changes. Both the Angasak and Amauligak temperature profiles have anomalies near the surface which cannot easily be explained. A least squares fit could be biased by these points which we feel would not necessarily represent the best fit to the data.

6.0 RESULTS OF COMPUTER SIMULATIONS

The number of input variables or parameters which must be assigned to the geothermal model is quite large, hence, the number of possible combinations of variables could not fully be explored in a study of this size. Therefore, a series of parametric analyses was undertaken, exploring those variables considered to be the most sensitive or subject to error. Thermal conductivities and specific heat parameters were fixed for each soil profile with values as suggested in the information provided with the service contract. The effects of salinity, surface temperature after inundation and initial boundary conditions were explored for each soil profile.

The results of the modelling for each site are presented in the following sections.

6.1 ANGASAK - MODELLING RESULTS

A total of eight (8) computer runs were undertaken to match the temperature profile observed for Angasak. Parameters were varied until "matches" for the observed temperature profile and thaw depths were achieved where possible.

A summary of all eight runs and the input parameters used is presented as Table 3.

6.1.1 Surface Temperature

After inundation, a mean sea bed surface temperature was imposed at the surface of the soil profile. Four analyses ANG-1 to ANG-4, inclusive, were run for surface temperatures of -1.5°, -0.3°, +0.0°, and +0.5°C, respectively. The temperature profiles from the computer simulations are presented in Appendix B as Figures B.1 to B.4, inclusive.

The observed temperature profile seemed to match run ANG-2 with a surface temperature of -0.3°C and a time after inundation of approximately 1600 years. Thaw depths predicted by the model were 30 m compared to 32 m observed, and this phase boundary is controlled

TABLE 3
Angasak - Soil and Geothermal Properties

Run No.	Layers	Thermal Conductivity (W/mK)		Specific Heat	Initial Temp.	Surface Temp.	Base of Permafrost	Moisture Content	Salinity	Unfrozen Water Content Parameters		Freezing Point
	(m)	kf	ku		(°C)	(°C)	(m)	(%)	(ppt)	P	Q	(°C)
ANG-1	0-45	4.0	3.2	0.18	-12.0	-1.5	412	24	35	20	0.5	-1.8
	45-850	2.1	1.8	0.18				24	22	15	0.7	-1.2
ANG-2	0-45	4.0	3.2	0.18	-12.0	-0.3	412	24	35	20	0.5	-1.8
	45-850	2.1	1.8	0.18				24	22	15	0.7	-1.2
ANG-3	0-45	4.0	3.2	0.18	-12.0	+0.0	412	24	35	20	0.5	-1.8
	45-850	2.1	1.8	0.18				24	22	15	0.7	-1.2
ANG-4	0-45	4.0	3.2	0.18	-12.0	+0.5	412	24	35	20	0.5	-1.8
	45-850	2.1	1.8	0.18				24	22	15	0.7	-1.2
ANG-5	0-45	4.0	3.2	0.18	-8.0	-0.3	412	24	35	20	0.5	-1.8
	45-850	2.1	1.8	0.18				24	22	15	0.7	-1.2
ANG-6	0-45	4.0	3.2	0.18	-16.0	-0.3	412	24	35	20	0.5	-1.8
	45-850	2.1	1.8	01.8				24	22	15	0.7	-1.2
ANG-7	0-45	4.0	3.2	0.18	-12.0	-0.3	412	24	35	20.0	0.5	-1.8
	45-850	2.1	1.8	0.18				24	10	9.0	1.2	-0.5
ANG-8	0-45	4.0	3.2	0.18	-12.0	-0.3	412	24	35	0.0	10.0	-1.8
	45-850	2.1	1.8	0.18				24	22	0.0	10.0	-1.2

by the change in salinity at this depth. The matched run for this case is shown in Figure B.9.

All other parameters were held constant and the soil and temperature conditions in run ANG-2 became the base case.

6.1.2 Initial Boundary Conditions

Three computer runs, ANG-2, ANG-5 and ANG-6, were undertaken to establish what effect variations in the initial temperature profile prior to inundation had on the predicted times for a match.

Observations today suggest thicknesses of ice-bonded permafrost occur up to 400 to 600 m at Angasak. The difficulty in estimating the initial temperature profile that existed lies with estimating the initial near surface temperature and the freezing point temperature at the base of the permafrost. No borehole information or salinity data exists at depth and therefore estimates had to be made. For our study, permafrost at depth was assumed to exist at -1.2°C or colder and the depth of permafrost was maintained at 412 m for all cases.

The initial surface temperatures examined were -8°, -12° and -16°C. The predicted temperature profiles are presented in Appendix B as Figure B.5, B.2 and B.6, respectively. Other parameters were maintained at base run values.

As can be seen, all three initial temperatures seem to match the observed profile at some time, but the time required is larger for the colder initial temperatures. For an initial temperature of -8°C, a matched temperature profile occurred at 1000 years, and for surface temperatures of -12° and -16°C, at 1100 and 1300 years, respectively. The matched runs are shown in Figure Nos. B.10, B.9 and B.11, respectively.

The importance of initial temperature does not appear to influence the shape of the temperature profile, but rather the time required to achieve a match. A reasonable bound on initial temperatures, therefore, will likely bound the time period an event occurred.

6.1.3 Salinity

Detailed geotechnical information, including salinity measurements, are available for the top 56 m at the Angasak wellsite. The top 32 m consists of a fine to medium-grained sand with salinity near 35 ppt. Below the sand are interbedded layers of sand, silts and clays with salinities ranging from 10 to 29 ppt. These layers are relatively thin in relation to the thickness of the permafrost zone and are difficult to represent in the geothermal model due to the dramatic decrease in time step required to maintain a stable run. Therefore, the interbedded soil layers below the unfrozen sand were grouped together and average geotechnical and geothermal properties assumed.

In the base case run, ANG-2, salinity below the unfrozen sand layer was assumed to be 22 ppt extending to the full depth of permafrost and the predicted temperature profile is shown in Figure B.2. Soil of this salinity has a freezing point of approximately -1.2°C (Figure 7). A second run, ANG-7, was undertaken assuming soil below the unfrozen sand had a lower salinity of 10 ppt and the predicted temperature profile is shown in Figure B.7. As can be seen, both runs match the observed temperature profile fairly well with the low salinity run producing a match at around 600 years, compared to the higher salinity base case run at 1100 years. The matched computer runs at the specific times cited are shown in Figure Nos. B.12 and B.9, respectively.

The effects of a discrete freezing point, corrected for the temperature depression of salinity, was investigated and the results presented in Figure B.8. As can be seen, the shape of the predicted temperature curve does not match the observed profile very well. This is strong evidence to the effect that freezing in saline soils likely does not occur at a discrete temperature, but is more correctly a function of unfrozen water content and temperature.

6.2 AMAULIGAK - MODELLING RESULTS

A total of six (6) computer runs were undertaken to match the temperature profile observed for Amauligak. Parameters were varied until "matches" for the observed temperature profile and thaw depths were achieved.

Although no soil stratigraphy is available, comparison of the Angasak and Amauligak temperature profiles suggest there may be a phase change around 45 m at Amauligak. This would correspond to a fairly high salinity between 30 and 35 ppt, in the upper 40 to 50 m. As the Angasak data revealed roughly 32 m of high salinity unfrozen sand, we have assumed a similar condition exists at Amauligak for the top 45 m. Our base case run, therefore, was for a two layered model with salinity of 30 ppt in the top layer and 10 ppt salinity at depth.

A summary of all six runs and the input parameters used is presented as Table 4.

6.2.1 Surface Temperatures

After inundation, a mean sea bed surface temperature was imposed at the surface of the soil profile. Two analyses, AMA-1 and AMA-2, were undertaken for surface temperatures of -1.5° and -1.0°C, respectively. The temperature profiles are presented in Appendix C as Figure Nos. C.1 and C.2, respectively.

The observed temperature profile that best matched the modelled temperature profile for run AMA-1 occurred with a surface temperature of -1.5°C and a time of approximately 6000 years. The matched run is shown in Figure C.7. The analyses for a surface temperature of -1.0°C did not match the observed profile.

All other parameters were held constant and the soil and temperature conditions in AMA-1 constituted the base case.

6.2.2 Initial Boundary Conditions

To establish the effect of different initial surface temperature conditions, three computer runs, AMA-3, AMA-1 and AMA-4, were undertaken.

Three initial surface temperatures were investigated; -10°, -14° and -18°C. The predicted temperature profiles are shown in Appendix C, Figure Nos. C.3, C.1 and C.4, respectively.

TABLE 4
Amauligak - Soil and Geothermal Properties

Run No.	Layers	Thermal Conductivity (W/mK)		Specific Heat	Initial Temp.	Surface Temp.	Base of Permafrost	Moisture Content	Salinity	Unfrozen Water Content Parameters		Freezing Point
	(m)	kf	ku		(°C)	(°C)	(m)	(%)	(ppt)	P	Q	(°C)
AMA-1	0-30	2.5	2.0	0.18	-14.0	-1.5	580	24	30	20.0	0.6	-1.6
	30-990	2.5	2.0	0.18				24	10	9.0	1.2	-0.5
AMA-2	0-30	2.5	2.0	0.18	-14.0	-1.0	580	24	30	20.0	0.6	-1.6
	30-990	2.5	2.0	0.18				24	10	9.0	1.2	-0.5
AMA-3	0-30	2.5	2.0	0.18	-10.0	-1.5	580	24	30	20.0	0.6	-1.6
	30-990	2.5	2.0	0.18				24	10	9.0	1.2	-0.5
AMA-4	0-30	2.5	2.5	0.18	-18.0	-1.2	580	24	30	20.0	0.6	-1.6
	30-990	1.5	2.0	0.18				24	10	9.0	1.2	-0.5
AMA-5	0-990	2.5	2.0	0.18	-14.0	-1.5	580	24	30	20.0	0.6	-1.6
AMA-6	0-990	2.5	7.0	0.18	-14.0	-1.5	580	24	10	9.0	1.2	-0.5
AMA-7	0-30	2.5	2.0	0.18	-14.0	-1.5	580	24	30	0	10.0	-1.6
	30-990	2.5	2.0	0.18					10	0	10.0	-0.5

Observations today suggest ice-bonded permafrost thicknesses in the general area vary up to 600 to 700 m near Amauligak (Judge et al, 1987). Surface temperatures before submergence have been assumed to vary linearly with depth to the base of permafrost. No borehole information exists at the base of the permafrost, but we have assumed permafrost exists below -0.5°C and extends to 580 m.

As can be seen, all three initial temperature conditions produce matched runs, but the time required to achieve the match is longer for colder starting conditions. This is the same result as found for the modelling of the Angasak data.

For an initial temperature of -10°C, a matched run occurred after 5500 years and for surface temperatures of -14 and -18°C, at 6500 years and 7000 years, respectively. The matched runs are shown in Figure Nos. C.8, C.1 and C.9.

6.2.3 Salinity

Detailed geotechnical information is proprietary and unavailable for this study. Reviewing data for Angasak and inspection of the shape of the observed temperature profile, it is postulated a surficial unfrozen zone of high salinity soil exists within the top 45 m at Amauligak.

Because of the uncertainty of soil conditions at the site, three models were examined; a uniform 10 ppt salinity profile, a uniform 30 ppt salinity profile, and a two layered system of 30 ppt salinity soil over a low 10 ppt salinity soil, the latter constituting the base case. The predicted temperature profiles are presented in Figure Nos. C.6, C.5 and C.2, respectively. As can be seen, after 10,000 years, the 30 ppt salinity profile has not come close to matching observed conditions. The two layer system and the 10 ppt uniform profile produced matched runs at approximately 6500 and 6000 years, respectively. These matched runs are shown in Figure Nos. C.7 and C.10. If our hypothesis of a two layered system is valid, 45 m of thaw would have occurred at this time, which would be determined by the change in salinity at the layer boundary. If the 10 ppt profile reflects real conditions, the sea bed temperature is below the freezing point of the soil and the permafrost is not degrading and will someday be in equilibrium.

One additional analysis, AMA-7, was run for the Amauligak profile for a discrete freezing point two layered system. Salinity was accounted for only in depression of the freezing point, but phase changes occurred entirely at one discrete temperature. The computer run is shown in Figure C.11 for different times and an approximate match is shown in Figure C.12. As can be seen, the time predicted to match the profile for a discrete freezing point is approximately 1650 years, three times faster than when salinity is handled more precisely.

7.0 DISCUSSION

From the previous analyses, the time to inundation appears to be very different for the two sites. The shape of the Angasak temperature profile suggests a fairly recent time since inundation while the Amauligak temperature profile is near isothermal, suggesting an advanced state of permafrost degradation. Referring to the work by Hill et al (1985) with a relative sea level curve produced by radio carbon dating of peat and the identification of spore species as shown on Figure 2, time from inundation at Angasak (6.7 m of water) is estimated to be 1150 years and at Amauligak (32 m of water), the time is estimated to be 6000 years. The geothermal model results are very consistent with these values and variations in either direction can be accounted for by uncertainty in certain input parameters.

Reasonable estimates of a mean surface sea bed temperature are essential in order to match the observed temperature profiles. The difficulty with assessing this parameter is that it is assumed as a mean value for all of the submergence period. Present sea bed temperatures may, however, not reflect the mean value if the sea was colder or warmer in the past.

Initial boundary temperatures appear important in establishing the time since marine transgression. Warmer or colder start conditions tend to accelerate or deccelerate the time to match present day conditions but do not seem to dramatically affect the shape of the temperature profile. This, however, may only be an observation for the upper permafrost zone and colder or warmer start conditions may affect the base of the permafrost to a greater extent. The present available temperature profiles only reflect between 15 and 50 percent of the permafrost thickness.

Salinity appears to be one of the more critical soil parameters, as it governs both the freezing point and the unfrozen water content function which has a dramatic impact on the time aspect of permafrost degradation. In addition, variation in salinity within layers introduces the possible complexity of having unfrozen and frozen soil layers interbedded at isothermal temperature conditions. If salinity were ignored in selecting unfrozen water content parameters, as has been done in the past with simple analytical or closed form solutions, then the permafrost would appear to warm up much quicker and unreasonably short times for marine transgression would be predicted. The geothermal modelling undertaken by Taylor and Judge (1988) for the Angasak site did not account for latent heat or the effects of salinity and this is thought to be the main reason their estimate of time since marine transgression is quite low (i.e. 300 years). For roughly the same boundary conditions, our study produced a time since transgression of 1100 years.

Variations of thermal conductivity are better understood, although still difficult to measure, but were not explored in this study due to time constraints. Changes in thermal conductivity will likely alter the time to achieve a matched run as well as the other parameters mentioned.

8.0 CLOSURE

In summary, geothermal modelling appears to be a useful tool in recreating past geological events, particularly marine transgression. It is of paramount importance, however, to correctly model the gradual phase change in saline soils. Simulations using a simple discrete freezing point will greatly underestimate the time of marine transgression. The results of this study appear to match the estimate of times for marine transgression on the Beaufort Shelf made by other very different methods. More complete geotechnical information and measured temperature profiles would be useful to minimize the number of estimated input parameters that would have to be made and would likely improve the results.

Respectfully submitted,

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RS/jlw/G231

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APPENDIX A

THERM1 USER'S MANUAL FOR GEOTHERMAL MODEL

NIXON GEOTECH LTD

BOX 9, SITE 9, RR6
Calgary, Alberta, Canada T2M 4L5
phone: (403)-226-0481

1-D GEOTHERMAL
PROGRAM (THERM1)

DESCRIPTION AND
USER'S MANUAL

NIXON GEOTECH LTD.,

Box 9, Site 9, R.R.6
Calgary, Alberta
Canada
T2M 4L5

November, 1989

VERSION 89-2

1. DESCRIPTION

The program THERM1 is written to solve one-dimensional heat transfer problems in soils with freezing or thawing. It is written in double precision FORTRAN 77. The units are SI, with degrees Celcius, metres and thermal conductivity in cal/cm day C. The main features of the program include:

1. *Finite Difference Rectangular Grid.* An Alternating Direction Explicit method is used to solve for temperatures at each time step. The method is stable and accurate for large values of the time step, and thereby greatly reduces computing time. Time steps are normally specified to be around 1 day, and output can be requested every 10-30 days as required.

2. *Phase Change.* The program handles freezing or thawing by assigning an exponential relationship between unfrozen water content and temperature for each specified material type. Phase change can be specified to occur over a very narrow range of temperatures if desired. A range of unfrozen water content functions can be specified to cover gravels, sands, silts, clays and saline soils, by varying two input parameters for each layer defined by the user. A worksheet included with the data disk illustrates the different forms of the unfrozen water content curve that can be simulated by the exponential function used by the program.

3. *Variable Thermal Properties.* Up to 12 different materials having quite different thermal properties can be specified (i.e. soil, peat, insulation, concrete, etc.). Each material is assigned frozen and thawed thermal conductivities, water content, heat capacity, density, and parameters for the phase change curve. The program will provide default values for dry density and specific heat for a saturated soil if the user leaves these inputs as zero.

4. *Surface Conditions.* The program can handle either a sinusoidal annual surface temperature variation, with a heat transfer coefficient to model the presence of snow cover in winter, or specified monthly variations of surface temperatures and snow cover thickness. A further surface temperature and pipe temperature option is to specify a table of discrete value of temperature and snow cover with time, and the program will interpolate between the tabulated values. A rigorous surface energy balance can be

carried out by providing 12 mean monthly values of solar radiation, wind velocity, and the program calculates the remaining energy balance terms such as evapo-transpiration and long-wave radiation. Finally, another option is available to specify average surface temperatures for the first 3 years, followed by an extreme set of surface temperatures in the 4th year. This is useful when studying the effects of an extreme winter or summer season on the ground thermal regime.

5. *Initial and base conditions*. The initial temperatures in the soil column can be specified as constant or linearly increasing with depth. If a geothermal gradient is specified, this is maintained at the base of the grid throughout the simulation, and is the normal base thermal boundary condition. An alternative base boundary condition is an isothermal condition (constant temperature), and this can also be specified by the user.

6. *Frost Heave*. If the soil is initially unfrozen, the program will automatically invoke a frost heave option, employing the Konrad-Morgenstern Segregation Potential method. The user defines a range of SP values for the soil, and the program predicts frost heave using a set of 5 user-defined values for the Segregation Potential parameter. This option is useful when studying the effects of gravel and insulation thicknesses on seasonal frost depth and heave.

7. *System*. The program THERM1 can be implemented on a PC-XT, PC-AT or 386 micro-computer. Data entry to the program is very straightforward, and usually involves as little as 10-15 lines of data in free or fixed format, which can be input in a very short time.

8. *Input Data*. The input data may be stored in a file, and THERM1 prompts for both input and output file names at the time of running. The data can be entered to a file using a standard text editor, or alternatively a special screen-entry data pre-processor included with the simulator can be used to create the data file for input to THERM1. This data pre-processor is known as 1DATA, and is invoked by typing the program name, and then supplying a file name for the formatted data file that will be prepared. This data file can be later edited using a text editor if desired. Several data files can be stored under the same file name, and a series of runs can be batched for processing at the same time.

9. *Output Data*. The user establishes the output interval, usually every few days, and the program writes out the temperature at all nodes, the depth to any phase boundaries

(i.e. thaw or frost depth), predicted frost heave, and the various components of the surface energy balance, if requested. The user is also asked at run-time for the name of an auxiliary file, to which the program will write out any frost or thaw depths, and every second temperature value with depth. This special output file can later be edited, and input to LOTUS 123, GRAPHWRITER or some other convenient plotting routine for routine plotting of the key elements of the output. An example of output from the program for frost depth near Boston Mass. is shown on Figure 1. Frost heave through the winter season can also be viewed using this output file. Figure 2 shows a plot of temperature profiles versus depth throughout the year for a discontinuous permafrost site. This was prepared from the auxiliary output file mentioned above, using a commercially available plotting package LOTUS GRAPHWRITER.

2. SUMMARY OF INPUT DATA FOR NIXON GEOTECH 1-D GEOTHERMAL SIMULATOR THERM1 (VERSION 89-2)

JOBNAM (80) - 80 characters to specify name of job
(A)

NLAYER,MUNIT,TSTART,LBFLAG
(2I3,F10.0,I3)

NLAYER - number of soil layers
MUNIT - enter 1 for metric thermal units
TSTART - start time for simulation in days after January 1,
LBFLAG - set equal to 0 for base geothermal gradient,
set equal to 1 for base constant temperature

TAV, A0, TI, TFIN, DTD, TIMOUT, GEO, TFRZ
(8F10.0)

TAV - mean temperature of surface sine wave (^{O}C)
T0 - amplitude of surface sine wave (^{O}C)
TI - constant initial soil temperature (^{O}C)
TFIN - final time in days
DTD - time step in days
TIMOUT - selected output time interval in days
GEO - geothermal gradient in ^{O}C/m, and
TFRZ- the freezing isotherm designated as a phase boundary (^{O}C)

Note: If TI = -100, the program requires (N+1) values for an arbitiary initial temperature profile, as follows:

TI(L), L = 1, N+1 TI is initial temperature ^{O}C, 12 values per line
(12F 6.0)

(SP(L), L = 1, 5), SIG0, a SP(L) = 5 values for SP parameter in mm2/day^{O}C
(7F10.0)

SIG0 = initial effective stress (kPa)
a = SP reduction factor (0.002 to 0.02kPa^-1)

JHEAT = 0 if a surface sine wave is used
(I1) = 1 if the surface met balance is required
= 4 for monthly temperature values, and extreme values used in 3rd year of simulation.

(The following data on this page only required if JHEAT >0)

SNOCON, SNOFAC

(2F10.0) - conductivity of snow (cal/C cm day) and a factor to reduce the standard met snow cover data.

Note: Typical snow conductivity = 50 - 75 cal/cm day^{O}C.

SNO1, SNO2, ALBS, ALBC, EF, EFS, GHF, GHINC (8F10.0)

SNO1 - day of first appearance of snow, measured from January 1
SNO2 - day of final melting of snow cover, measured from January 1
ALBS - albedo of snow surface
ALBC - albedo of summer soil surface
EF - Thornthwaite evapotranspiration correction factor(usually 0.33-0.5)
EFS - further correction factor depending on wetness of surface (normally 1.0 for wet) or moist surface)
GHF - initial greenhouse factor (typically about 0.83)
GHINC - annual increase in greenhouse factor (normally zero unless climatic change effects are of concern)

TAM(12)	(12F10.0)	12 monthly mean values of ambient temperature in (^{O}C) starting in January
WIN(12)	(12F10.0)	ditto for wind velocity in (k.p.h.)
SNO(12)	(12F10.0)	ditto for cumulative snow cover in (cm)
RAD(12)	(12F10.0)	ditto for solar radiation in cal/cm2.day

NOTE: If WIN(12) are specified to be 1000 kph, EF = 0 and RAD(12) = 0, then the program will apply the ambient temperatures directly to the soil or snow surface. This is the usual method of applying variable monthly temperatures to the ground surface.

Note: If JHEAT = 4, then enter a set of extreme monthly temperatures instead of WIND velocity. That is, the program will use the values input for wind velocity as the surface temperatures applied in the 3rd year.

APPENDIX A

SAMPLE PROBLEMS

The first sample problem involves calculating the seasonal frost depth at a waste disposal site in a town near Boston, Mass. The site is covered with 0.15 m thickness of fine-grained fill, and it is required to determine the frost penetration beneath the surface fill layer, in a season where relatively cold winter temperatures are experienced in the third year of simulation, with no snow.

The data file is as follows, involving 2 thicknesses of surface fill in the same data file, and the output plots show the predictions for the 0.15 m surface layer case. Note that 2 data sets are included in the same data file, FR-MASS.DAT .

```
 1-d frost depth and heave: Woburn Mass. 0.15M COVER, NO SNOW IN WINTER
  4  1 0.
12.,0.,12.,1200.,1.0,5.,0.020,-0.10
80.,80.,60.,40.,0.,0.,0.00
4
75.,1.
365.,1.,1.00,1.00,0.00,0.0,0.83,0.
-3.06,2.35,1.56,8.79,14.93,20.73,22.83,22.63,18.33,12.17,4.8,-1.04
-5.13,-4.23,1.56,8.79,14.93,20.73,22.83,22.63,18.33,12.17,4.83,-3.15
0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.
0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.
300.,360.,0.15,25.,2.0,0.22,0.,1.442
370.,364.,0.5,30.,5.,0.11,0.,1.602
370.,364.,1.2,30.,5.,0.11,0.,1.602
370.,364.,4.8,30.,5.,0.11,0.,1.602
 1-d frost depth and heave: Woburn Mass. 0.3M COVER
  4  1 0.
12.,0.,12.,1200.,1.0,5.,0.020,-0.10
80.,80.,60.,40.,0.,0.,0.00
4
75.,1.
365.,1.,1.00,1.00,0.00,0.0,0.83,0.
-3.06,-2.35,1.56,8.79,14.93,20.73,22.83,22.63,18.33,12.17,4.83,-1.04
-5.13,-4.23,1.56,8.79,14.93,20.73,22.83,22.63,18.33,12.17,4.83,-3.15
0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.
```

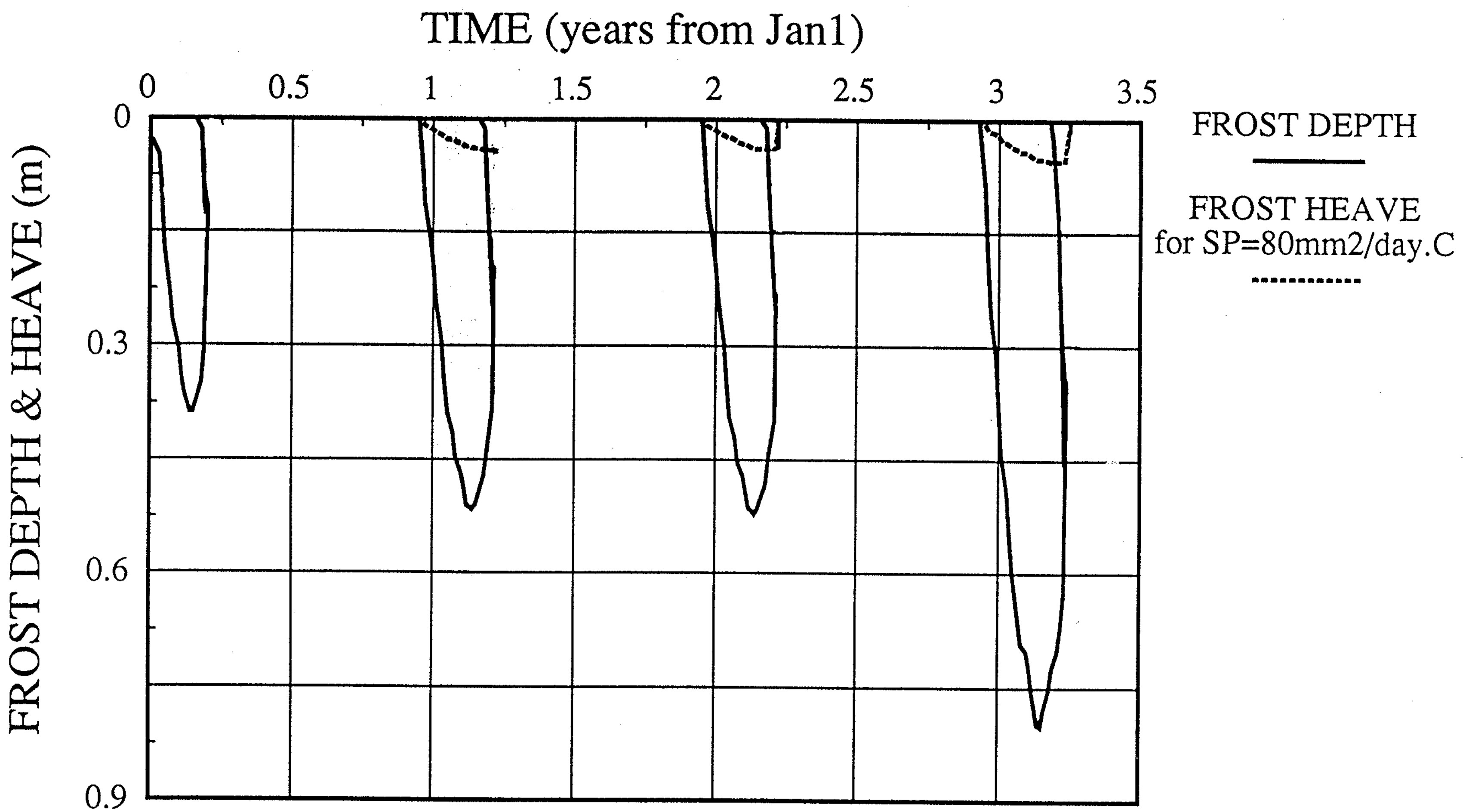
```
0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.
300.,360.,0.3,25.,2.0,0.22,0.,1.442
370.,364.,0.5,30.,5.,0.11,0.,1.602
370.,364.,1.2,30.,5.,0.11,0.,1.602
370.,364.,4.8,30.,5.,0.11,0.,1.602
```

The second sample problem involves a layer of granulite insulation 0.76 m in thickness, placed on a natural permafrost profile in an area near Norman Wells, NWT. The purpose of the simulation was to determine the effects of the insulation in retarding warming and long-term thermal degradation of the underlying warm discontinuous permafrost. The input data can be obtained from the long-term average meteorological air temperature data for Norman Wells, modified with an n-factor to obtain the ground surface temperature history throughout the year. Alternatively, as in this case, some Arctic Gas surface temperature predictions together with a "standard" snow cover profile were used to simulate the long-term permafrost response in this area. This set of boundary conditions is known from experience to result in a progressive deepening of the permafrost table in the long term, giving a thaw depth of 5-6 m deep in 20 years. The sample problem studies the effect of a surface insulating layer in slowing down this thaw. The simulation is set to run for 2000 days, but this can be extended if necessary.

```
1-d PAD DESIGN FOR SLOPE PROTECTION IN N.WELLS;.76m OF GRANULITE ON
P'FROST
  4  1      .000
   -1.000      .000    -1.000  2000.000     1.500    30.000      .020
-.150
1
   50.000     1.000
270.00120.00   .08   .90   .00   .00   .83   .00
-24.4,-18.,-12.8,-2.3,6.86,14.42,17.22,14.56,7.14,-3.2,-13.4,-22.
 999.0 999.0 999.0 999.0 999.0 999.0 999.0 999.0 999.0 999.0 999.0 999.0
43.2,50.8,40.6,7.6,0.,0.,0.,0.,0.,10.2,12.7,33.
0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.
   41.300    45.500     0.760      .000    10.000      .200      .200
1.000
   150.0    282.      0.15      5.      5.        0.80 0     0.0.
```

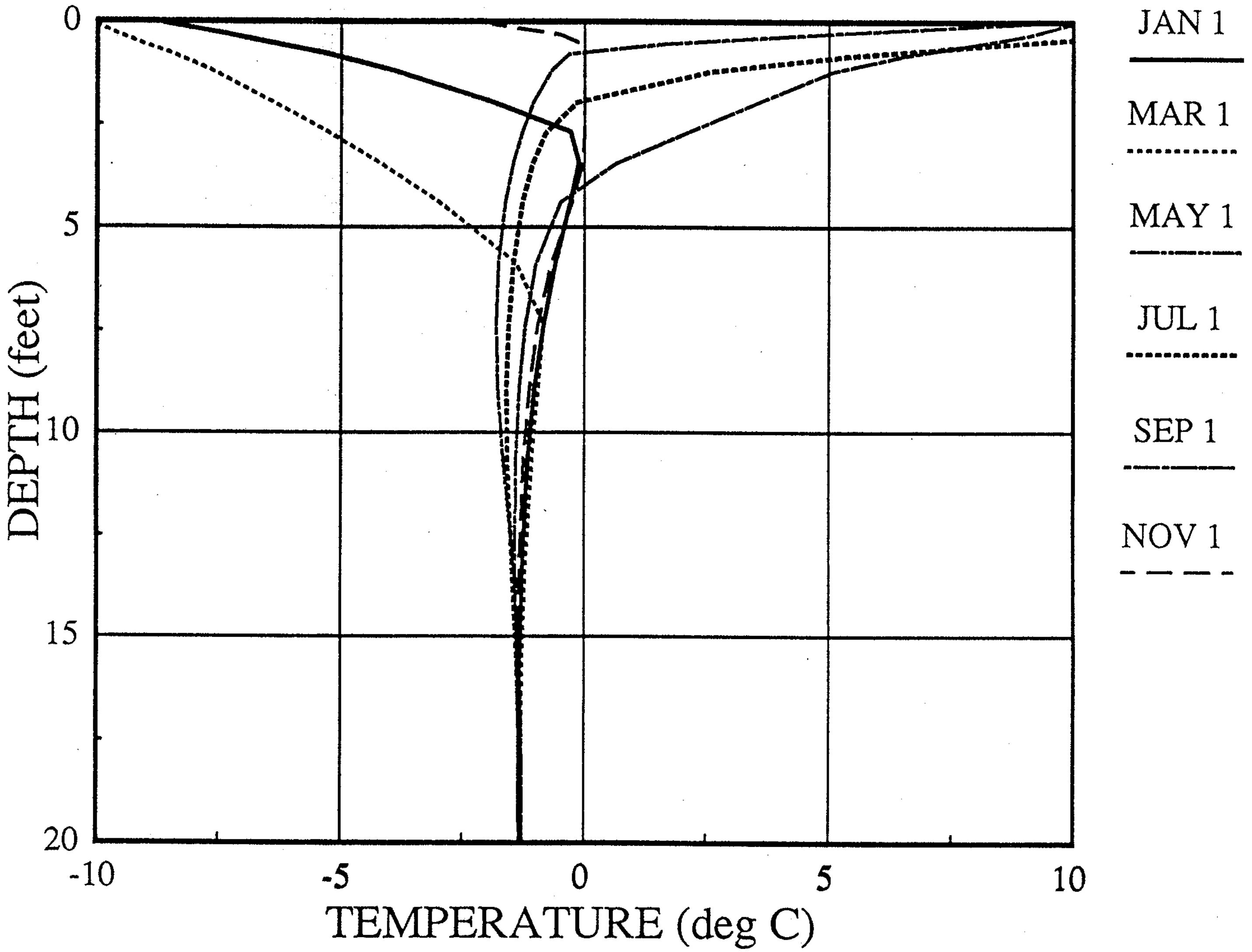
```
      320.       400.        1.2         23.     2.5          0.25       0.
0.0
      320.       400.        6.0         23.     2.5          0.25       0.
0.
```

DEPTH OF FROST AT WOBURN, MASS.,AVG & EXT. YEARS
0.15m DEPTH OF SANDY CLAY COVER; w=10% in-situ



WATER CONTENT IN SANDY CLAY COVER = 22%,GAMD=100
WATER CONTENT IN IN-SITU SILTY SAND = 10%,GAM=1.44
YEAR 3 IS EXTREME FREEZING INDEX

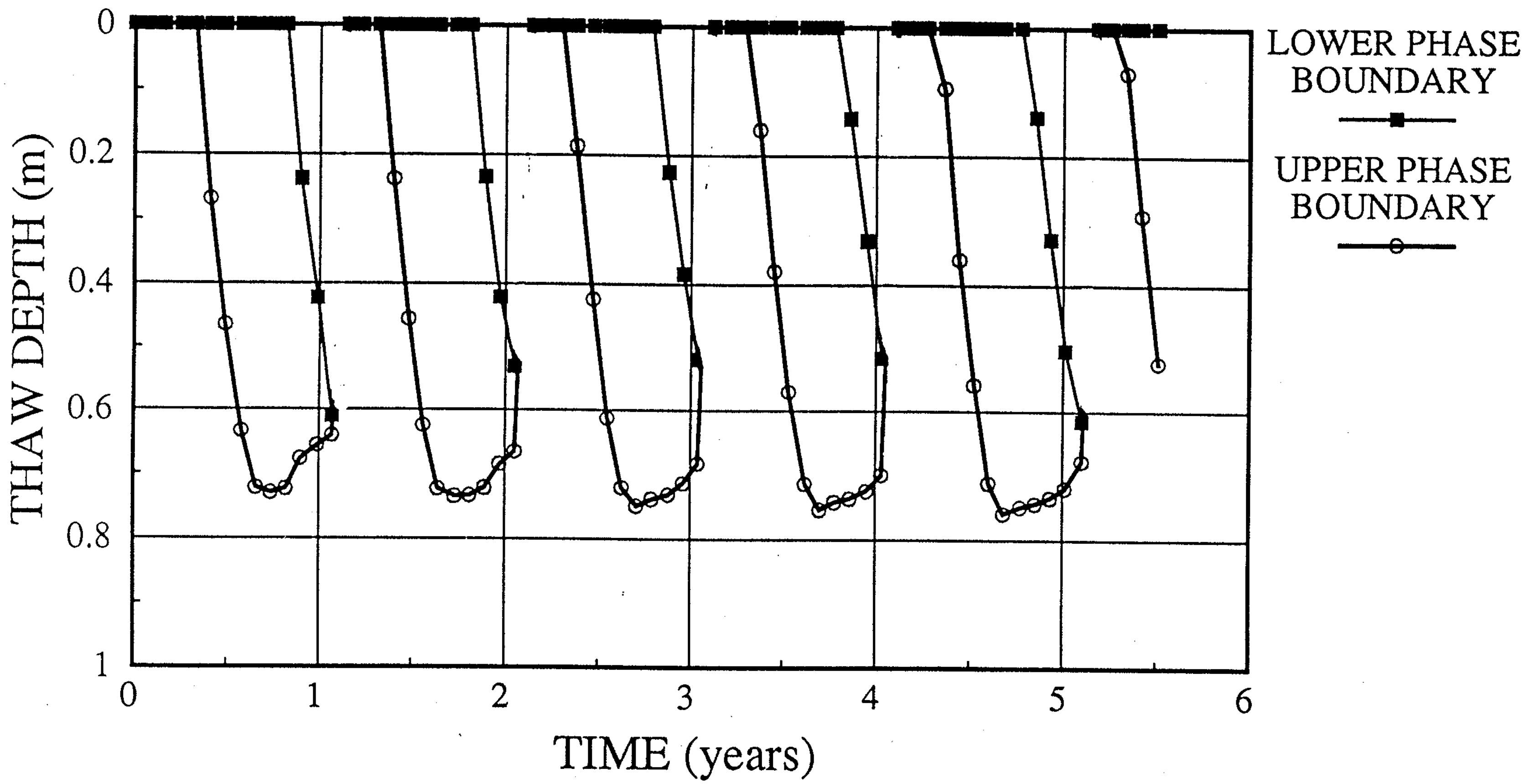
TEMPERATURE PROFILES IN DISCONTINUOUS PERMAFROST PREDICTED USING NIXON GEOTECH SIMULATOR



1 foot Peat over silt at 25% water content
Mean Temp = -1.3C, mean monthly surface temps
and snow cover values supplied by user

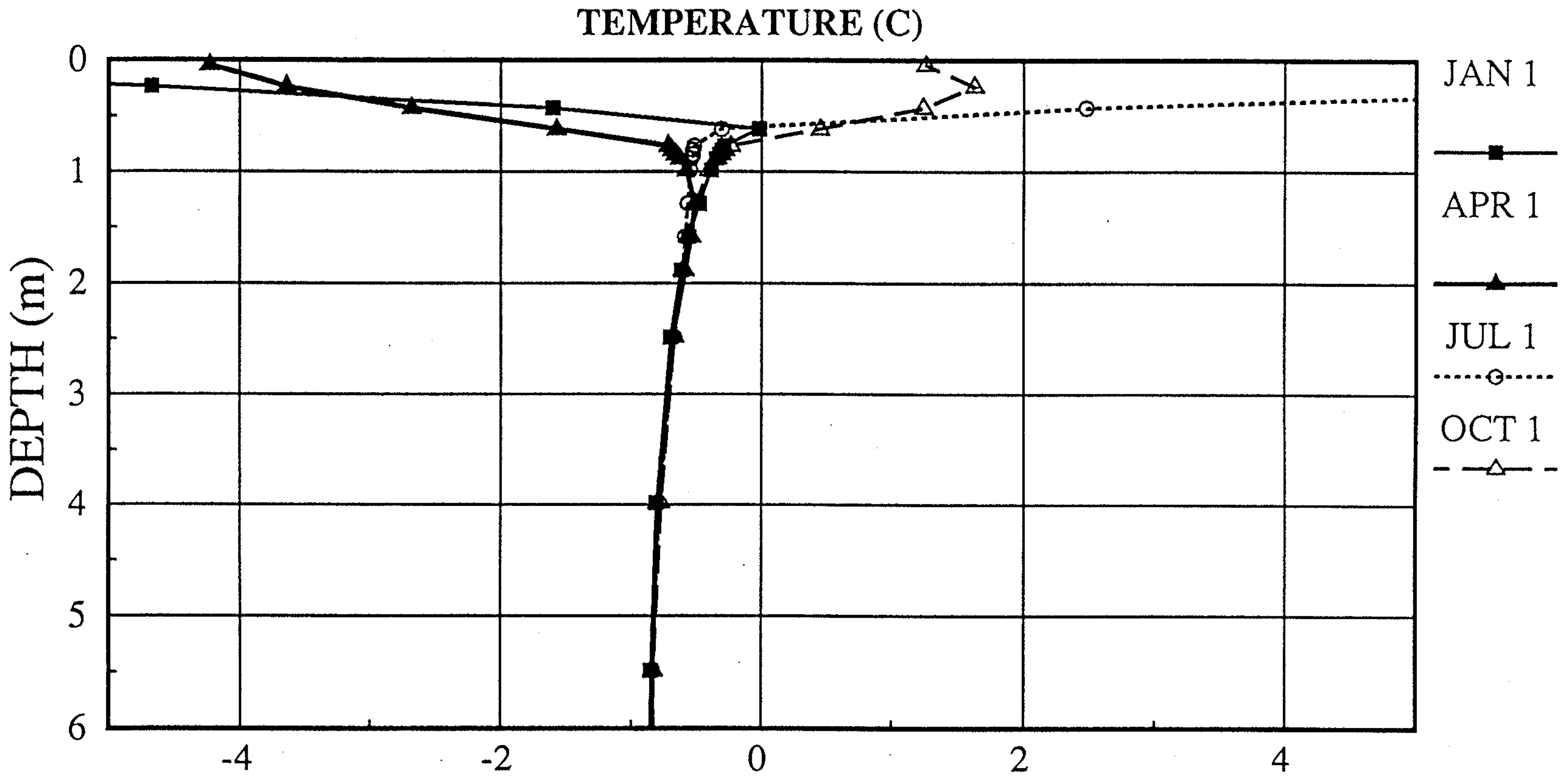
NOTE: This plot was prepared
from the auxiliary output file
generated by 1DDP, using
LOTUS GRAPHWRITER(not incl)

PREDICTED THAW DEPTH IN DISCONTINUOUS PERMAFROST WITH 0.76 m OF GRANULITE INSULATION



MEAN GROUND TEMPERATURE = -1.3C
SURFACE TEMPERATURES AND SNOW COVER FROM
ARCTIC GAS REPORTS ON GEOTHERMAL ANALYSIS

GROUND TEMPERATURES IN DISCONTINUOUS PERMAFROST WITH 0.76 m OF GRANULITE INSULATION



MEAN GROUND TEMPERATURE = -1.3C
SURFACE TEMPERATURES AND SNOW COVER FROM
ARCTIC GAS REPORTS ON GEOTHERMAL ANALYSIS

APPENDIX B

MODELLED TEMPERATURE PROFILES - ANGASAK

FIGURE B.1 ANG-1 SURFACE TEMPERATURE = -1.5°C

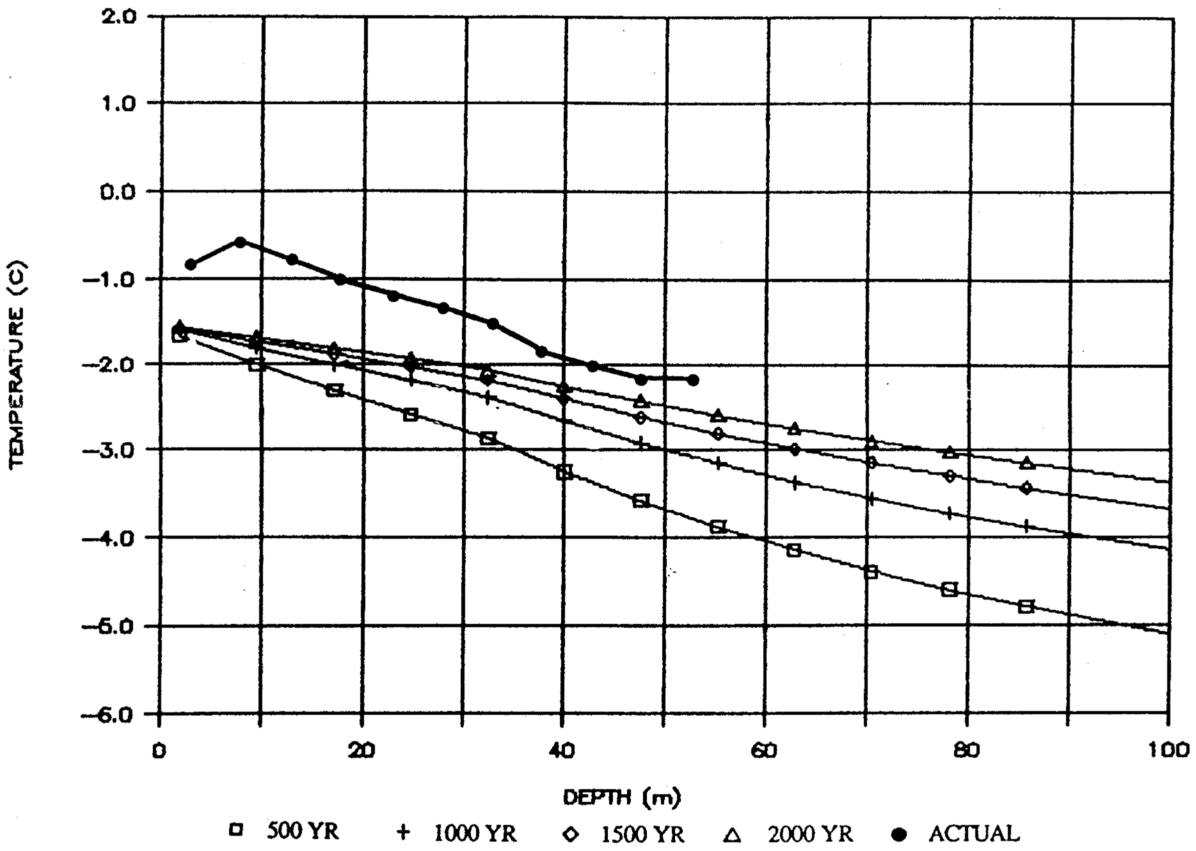


FIGURE B.2 ANG-2 SURFACE TEMPERATURE = -0.3°C (Base Case)

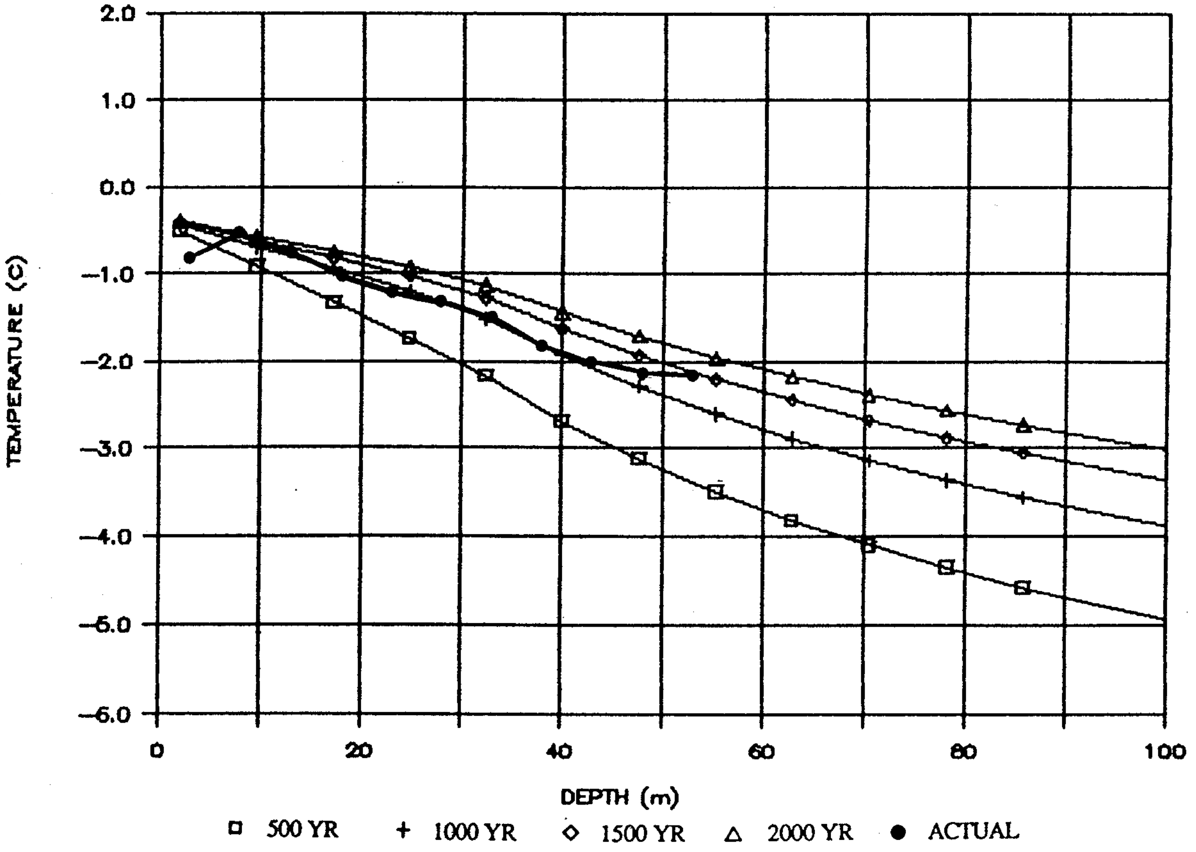


FIGURE B.3 ANG-3 SURFACE TEMPERATURE = +0.0°C

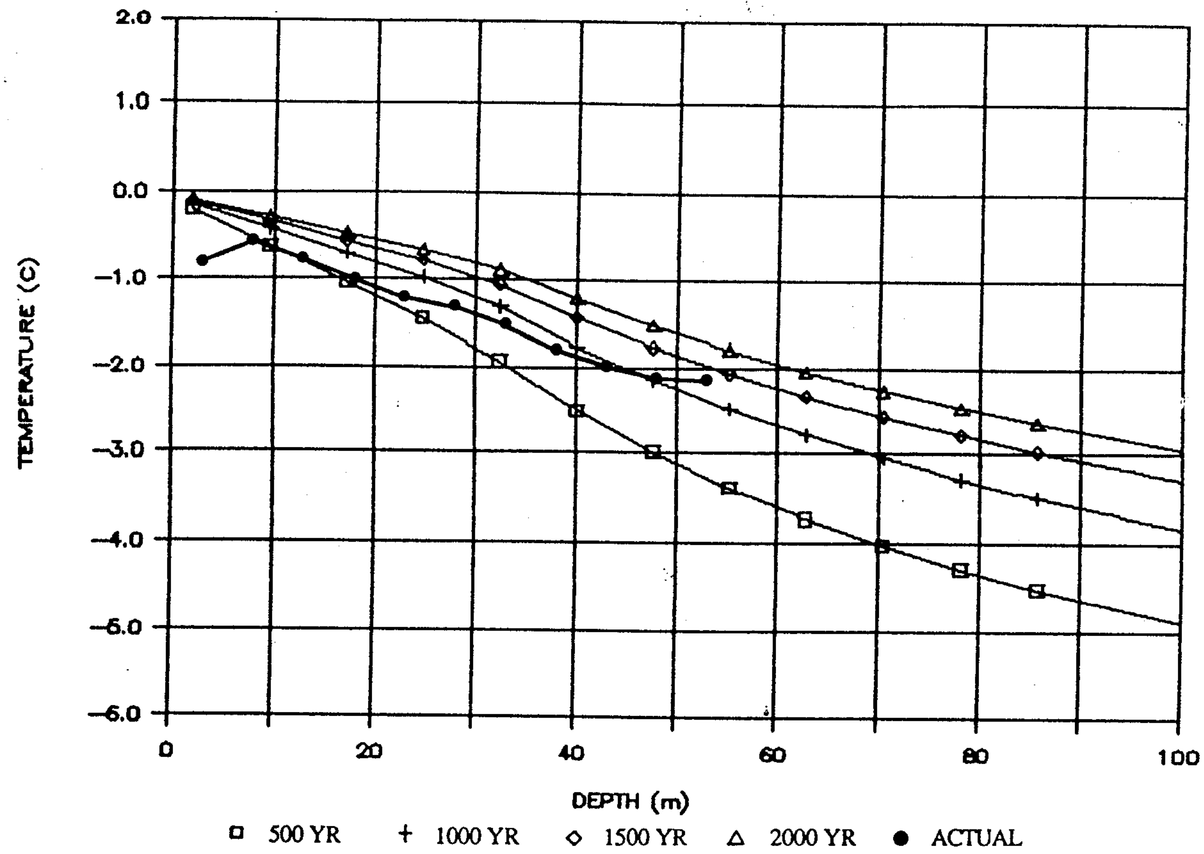


FIGURE B.4 ANG-4 SURFACE TEMPERATURE = +0.5°C

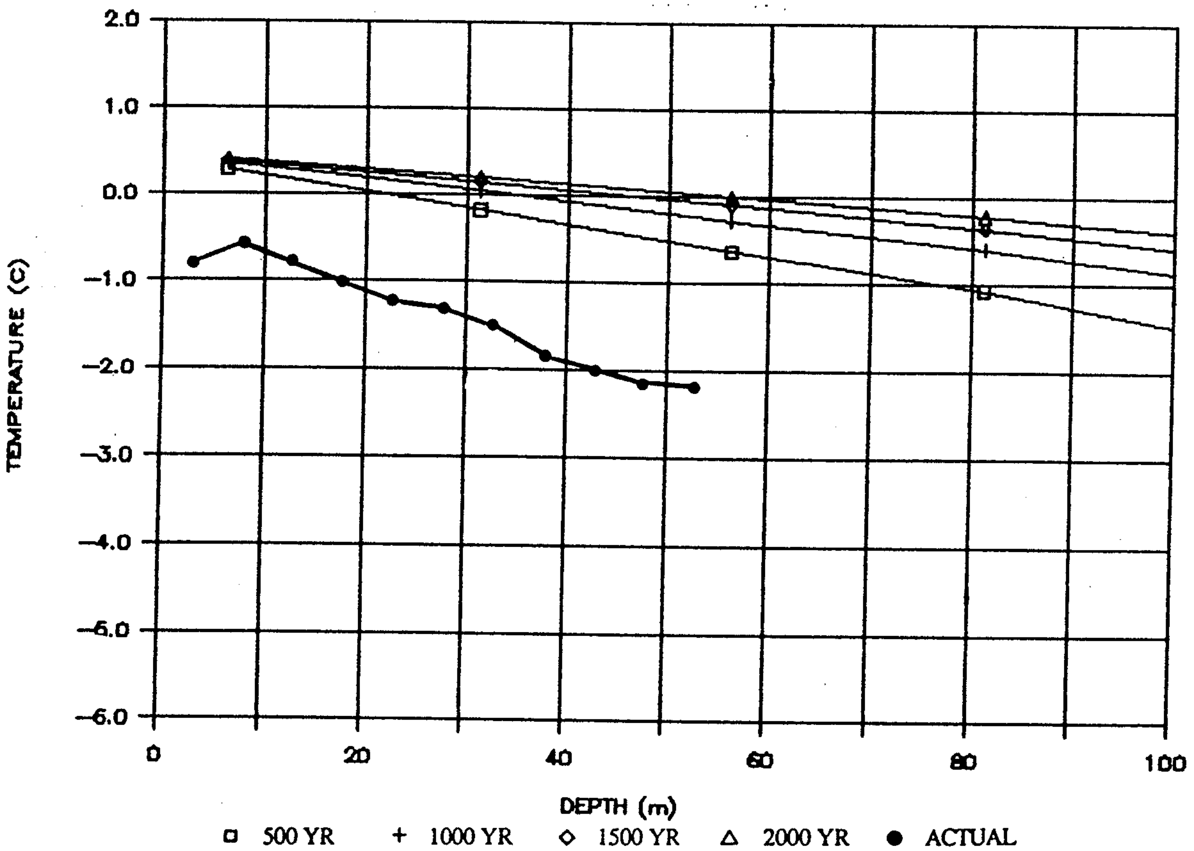


FIGURE B.5 ANG-5 INITIAL TEMPERATURE = -8.0°C

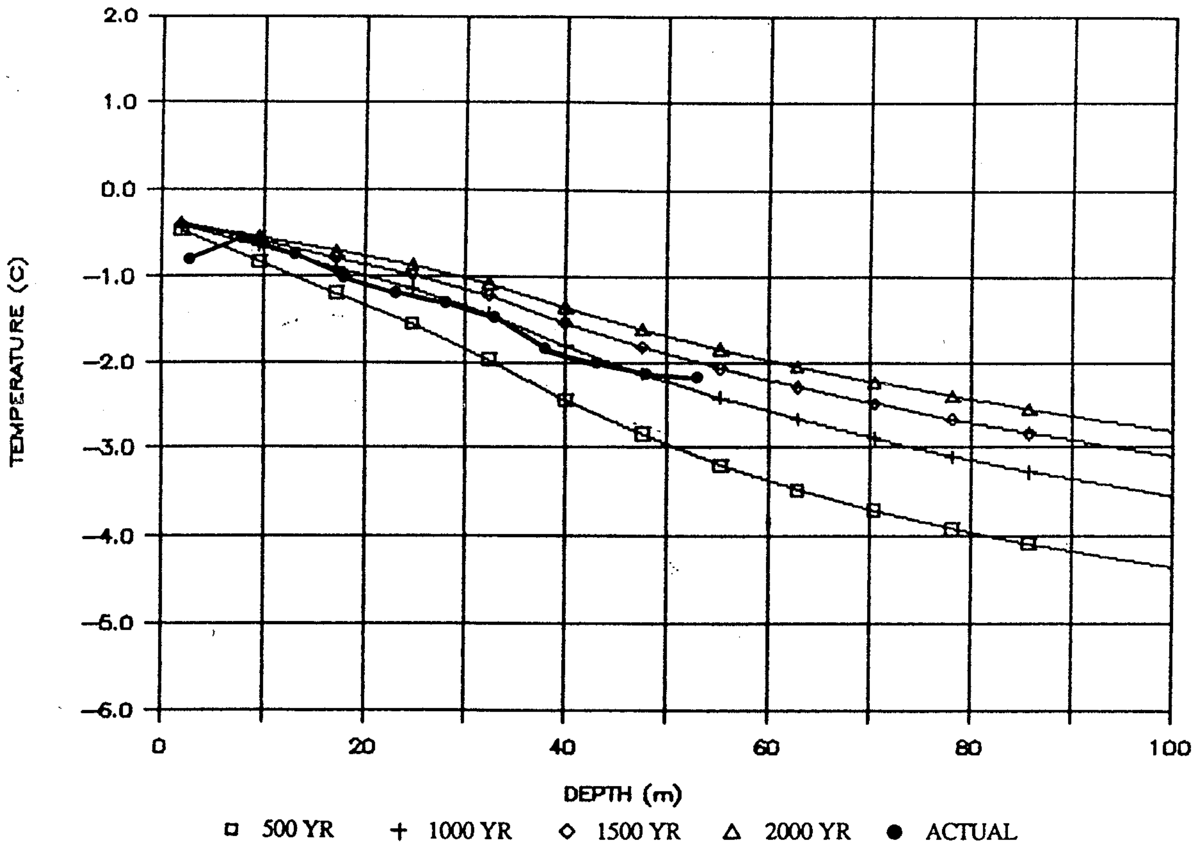


FIGURE B.6 ANG-6 INITIAL TEMPERATURE = -16.0°C

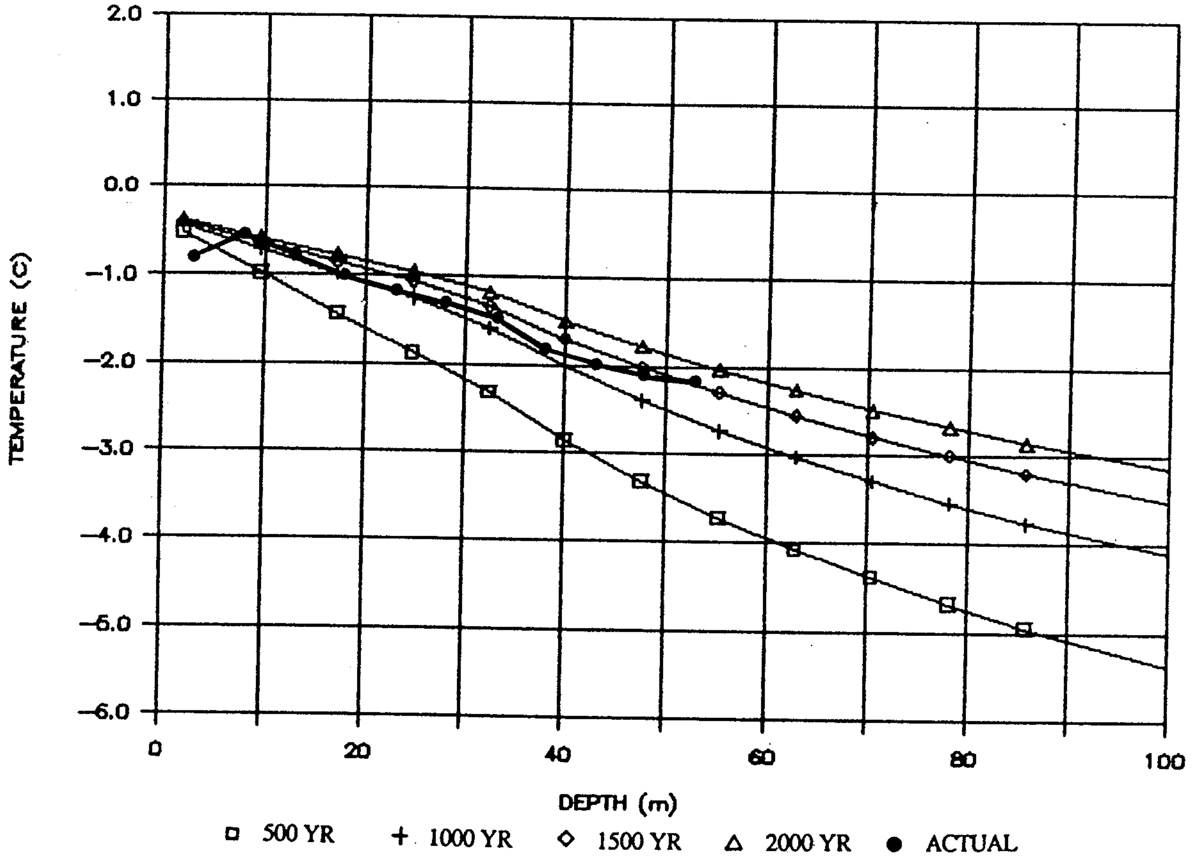


FIGURE B.7 ANG-7 LOW SALINITY AT DEPTH

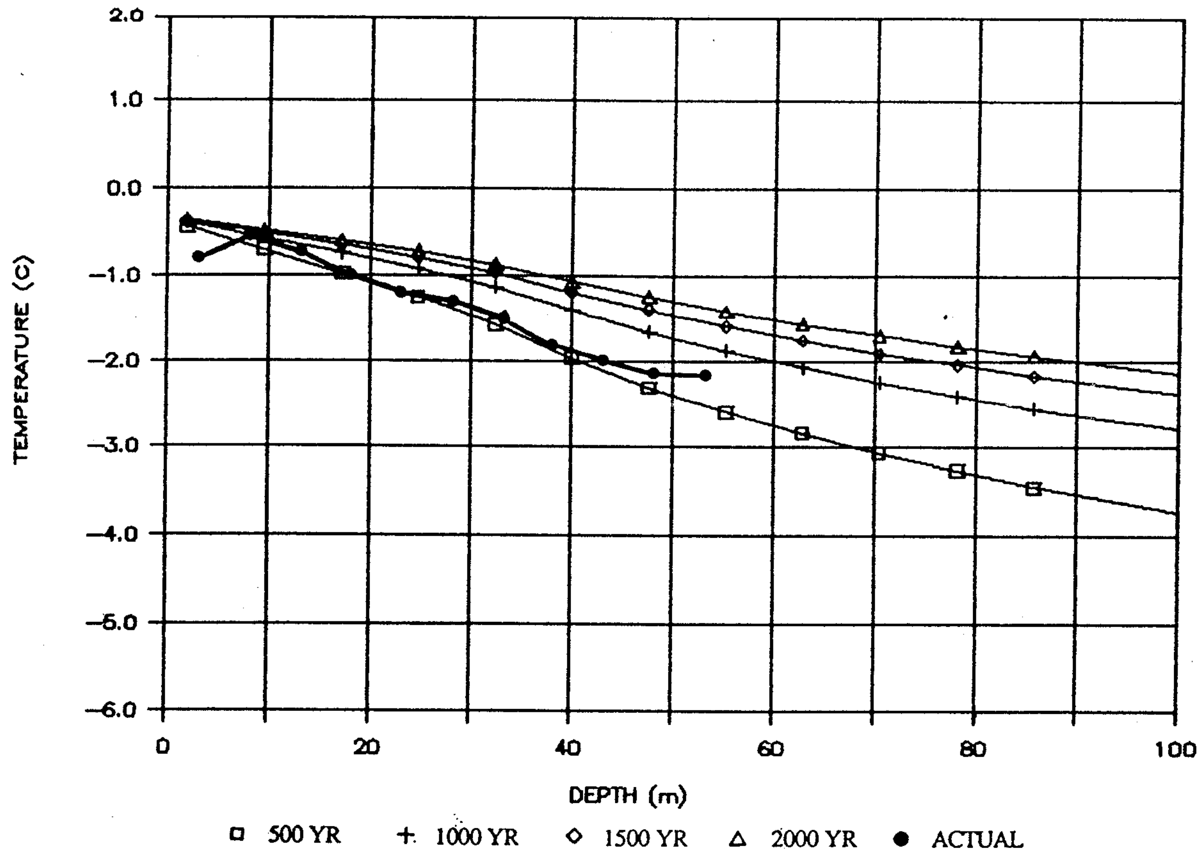


FIGURE B.8 ANG-8 DISCRETE FREEZING POINT

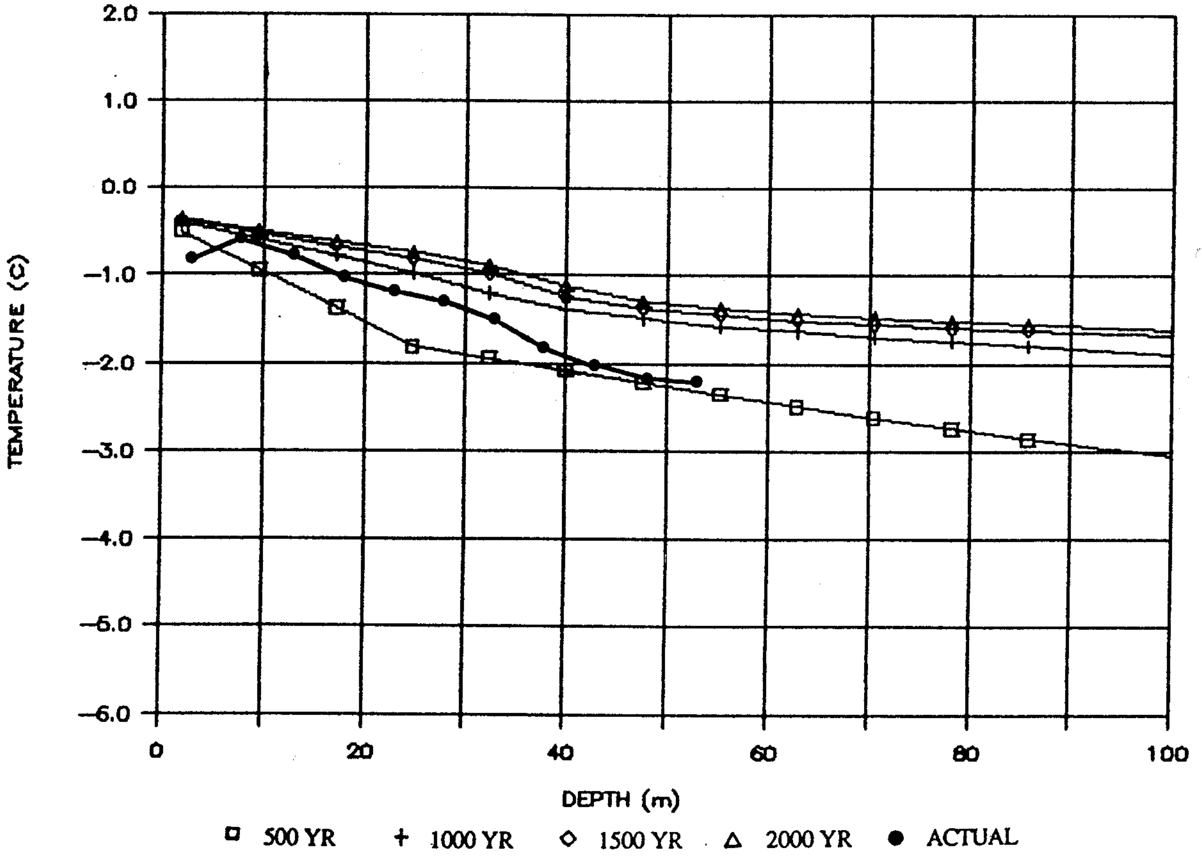


FIGURE B.9 ANG-2 1100 YEARS (Matched Run)

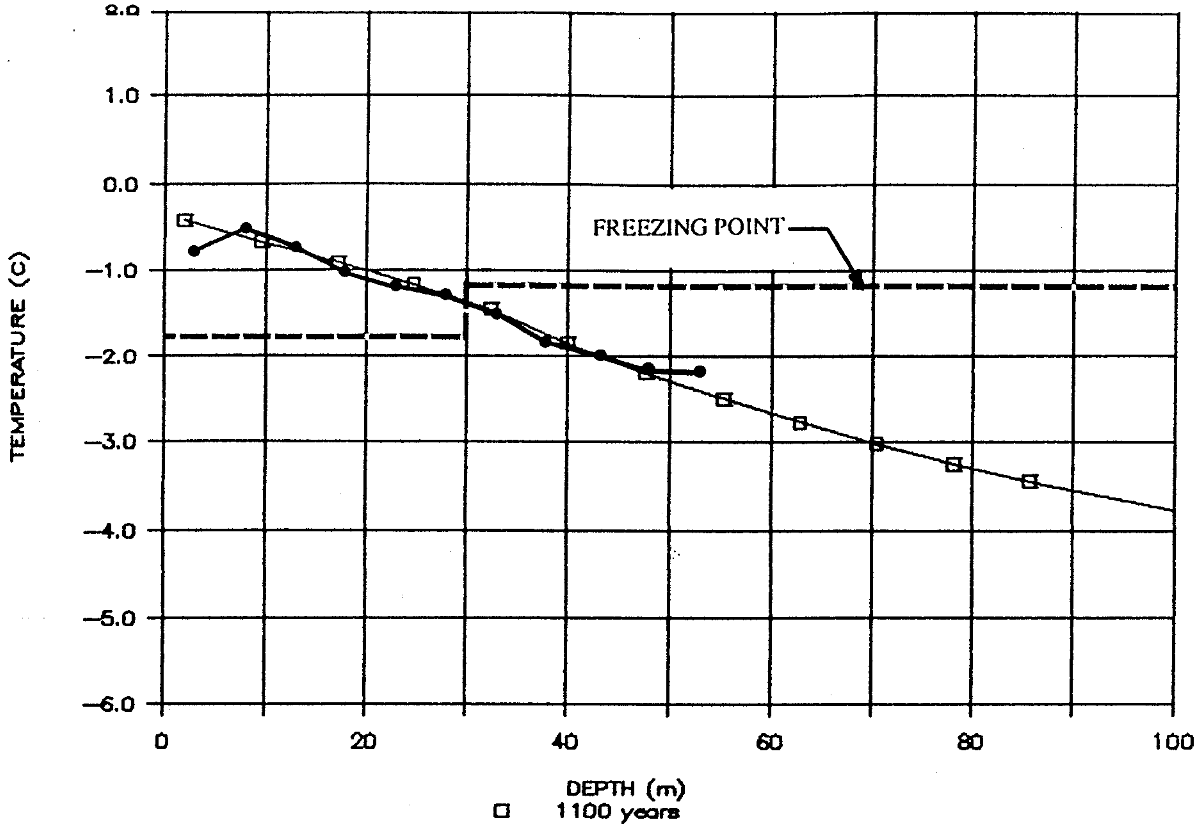


FIGURE B.10 ANG-5 1000 YEARS (Matched Run)

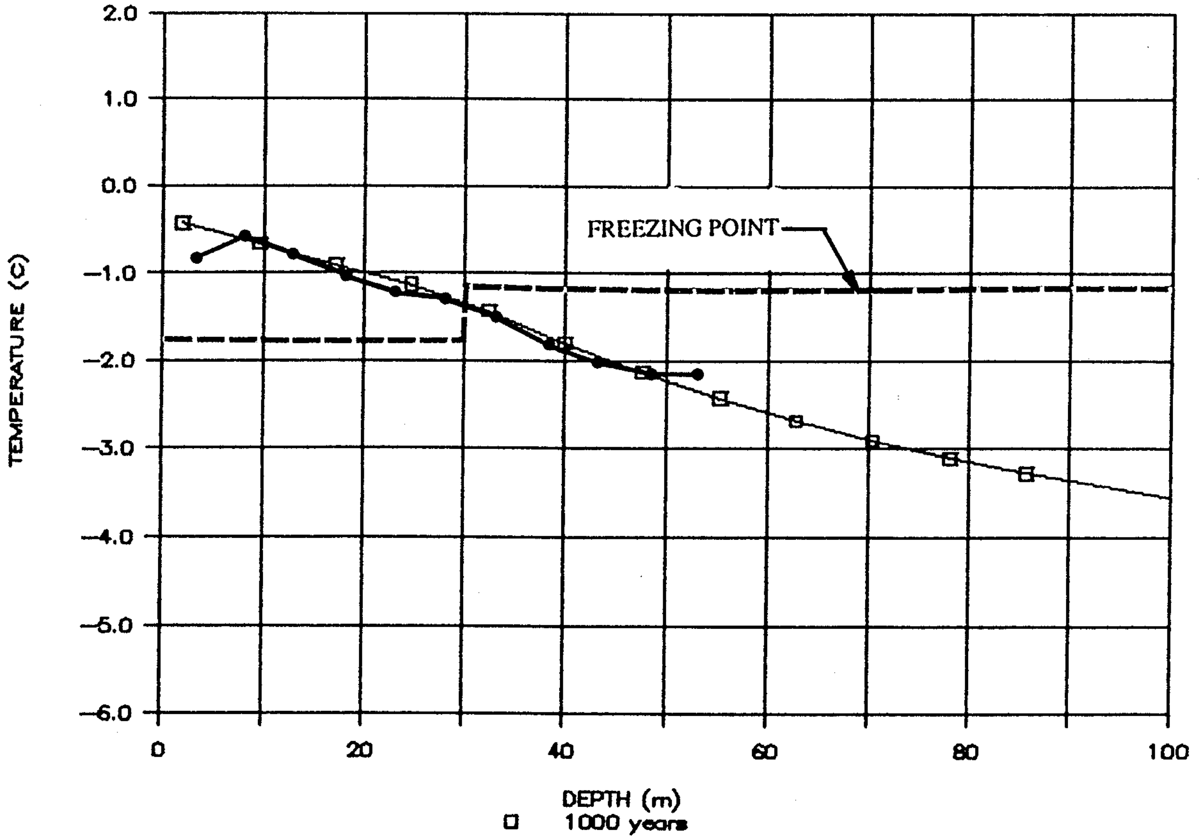


FIGURE B.11 ANG-6 1300 YEARS (Matched Run)

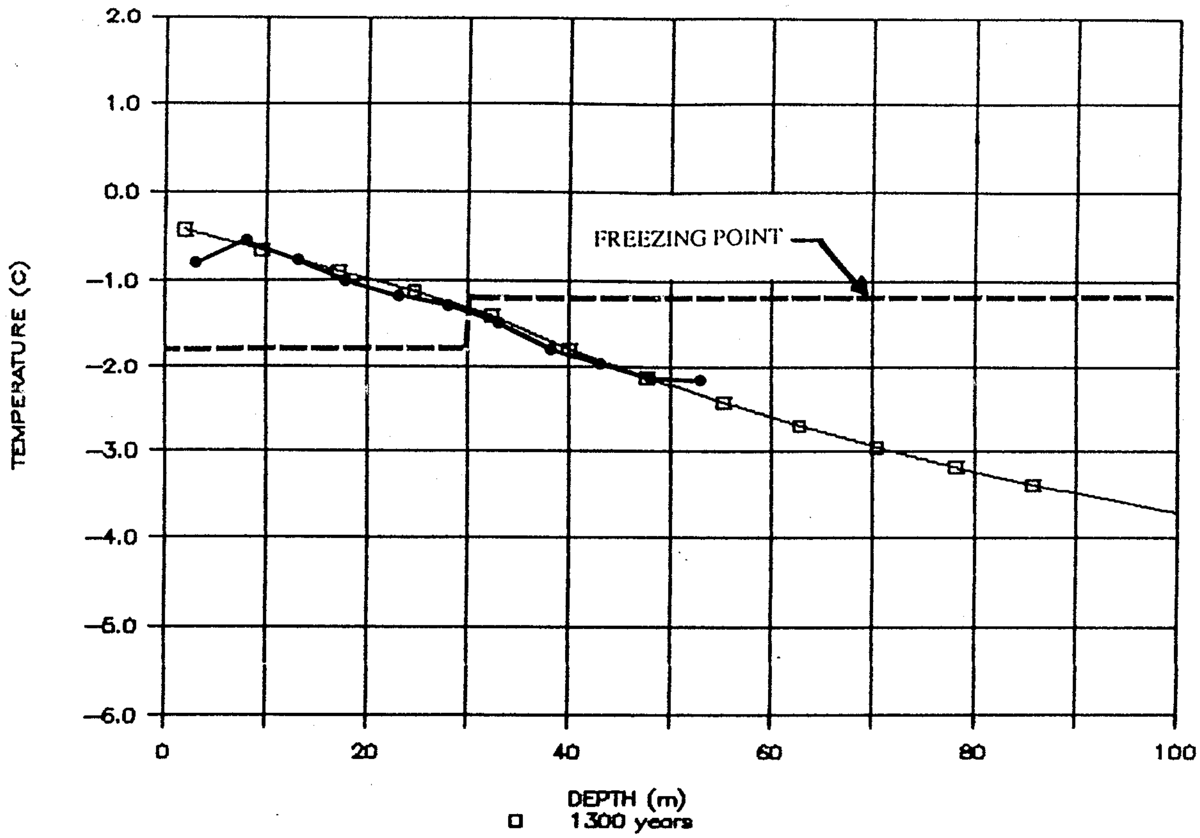
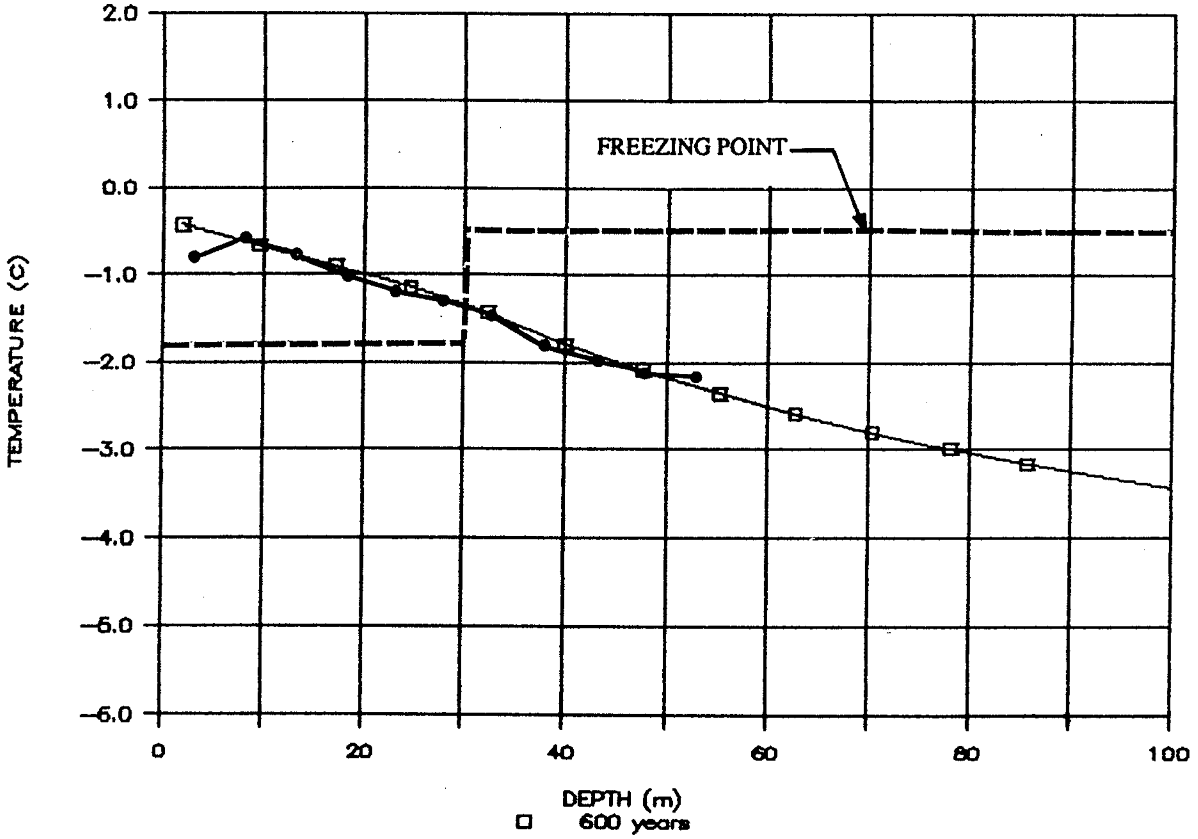


FIGURE B.12 ANG-7 600 YEARS (Matched Run)



APPENDIX C

MODELLED TEMPERATURE PROFILES - AMAULIGAK

FIGURE C.1 AMA-1 SURFACE TEMPERATURE = -1.5°C (Base Case)

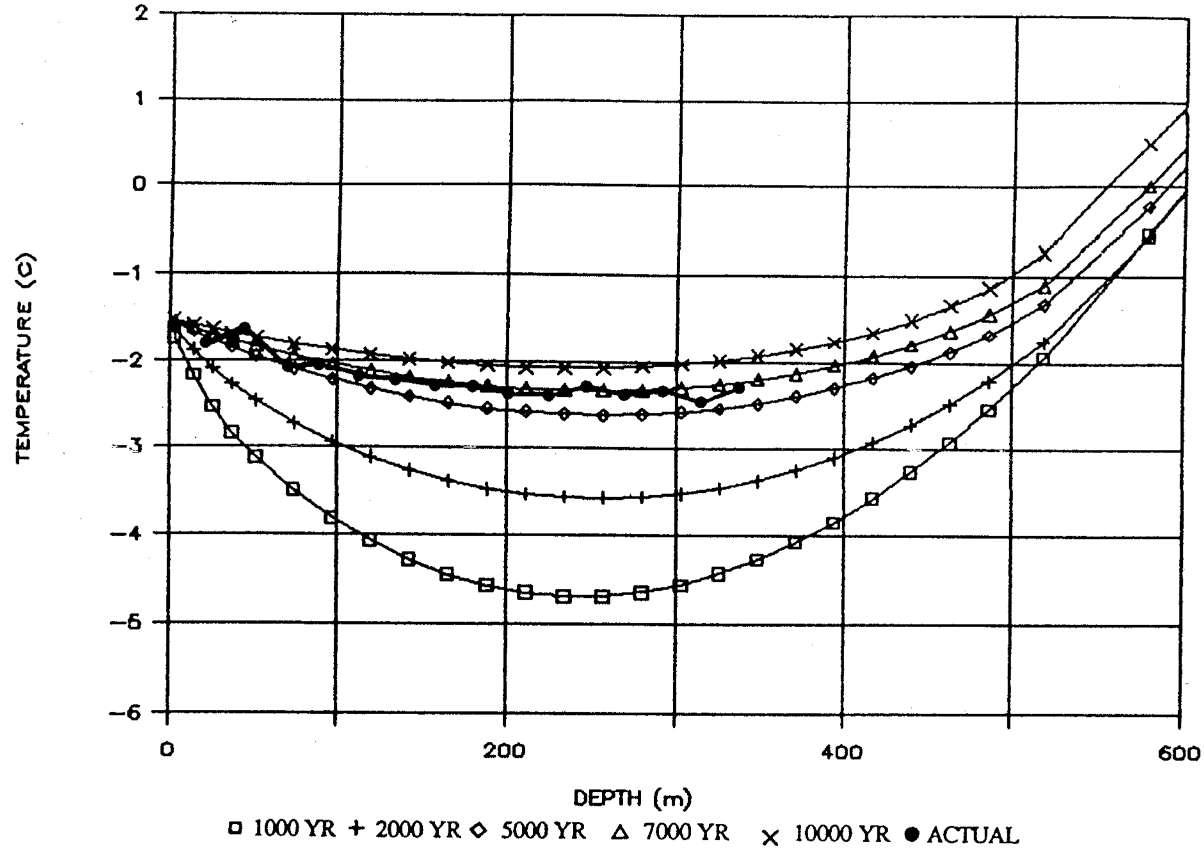


FIGURE C.2 AMA-2 SURFACE TEMPERATURE = -1.0°C

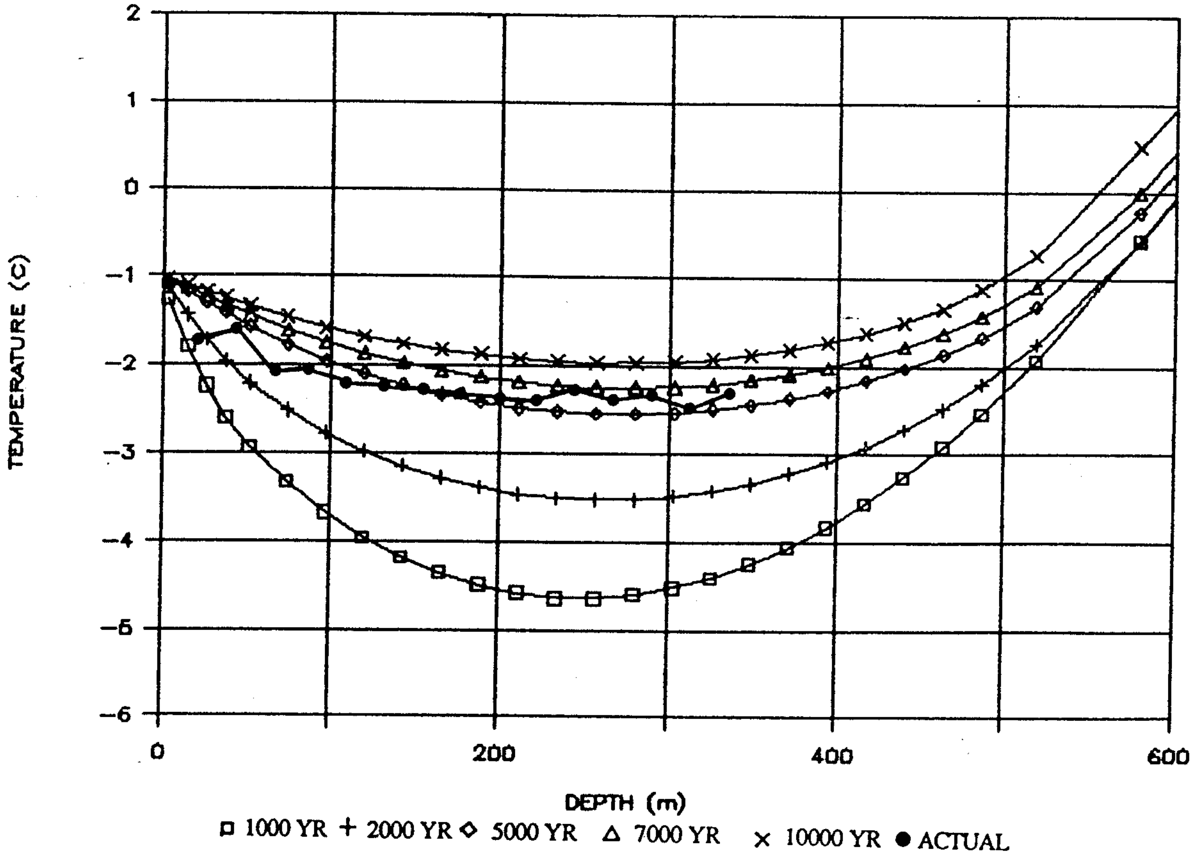


FIGURE C.3 AMA-3 INITIAL TEMPERATURE = -10.0°C

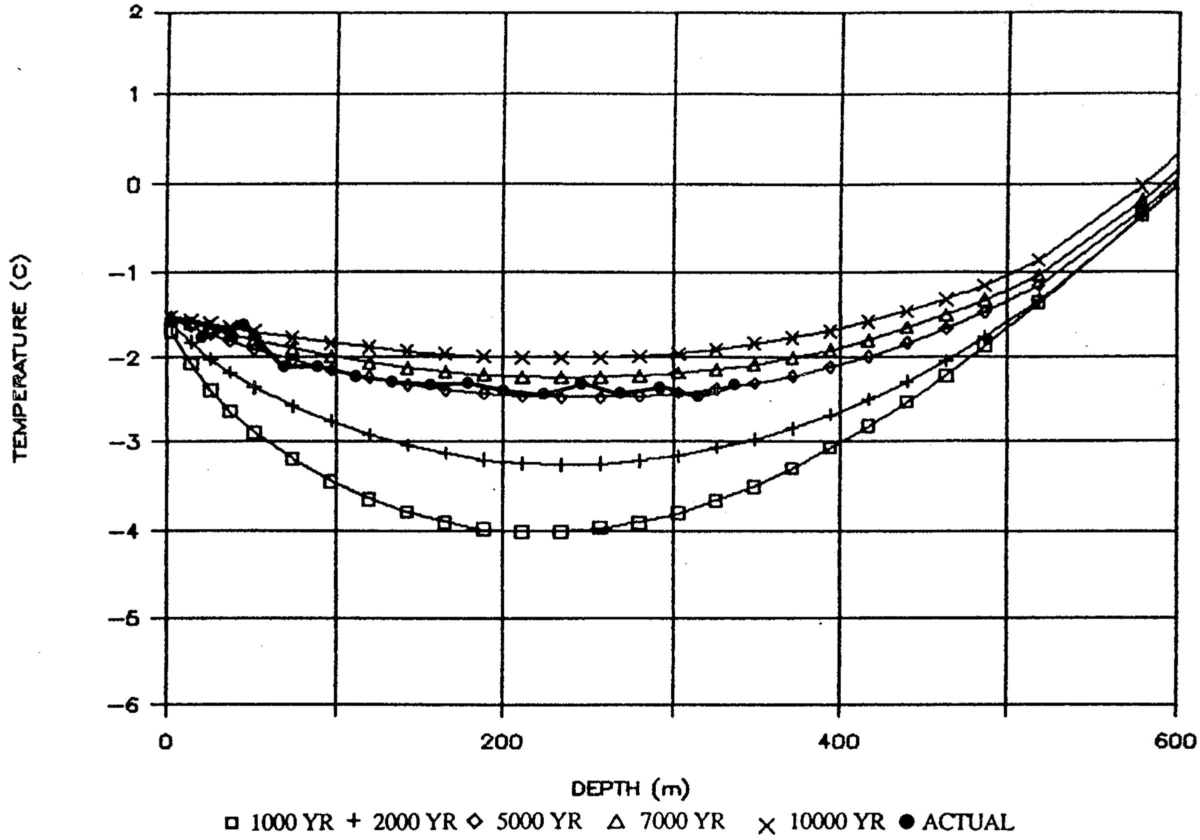


FIGURE C.4 AMA-4 INITIAL TEMPERATURE = -18.0°C

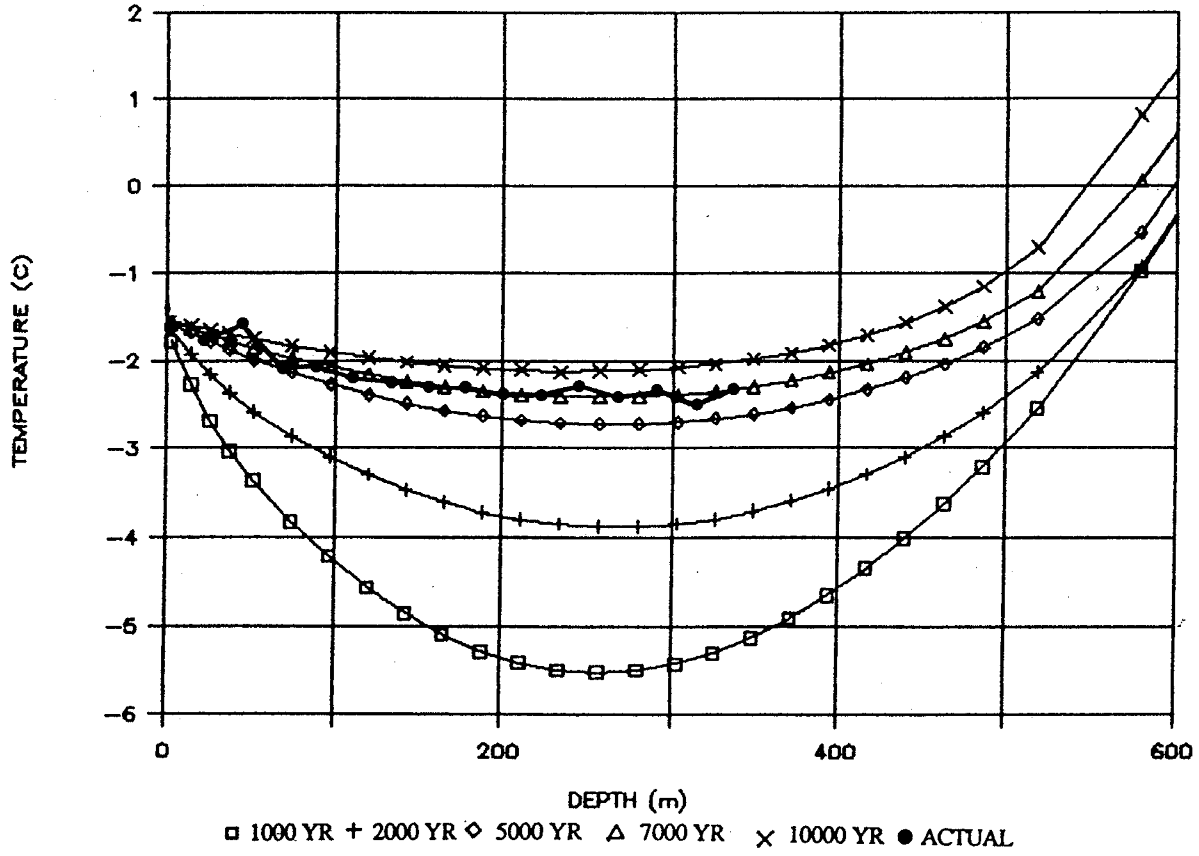


FIGURE C.5 AMA-5 UNIFORM SALINITY (30 ppt)

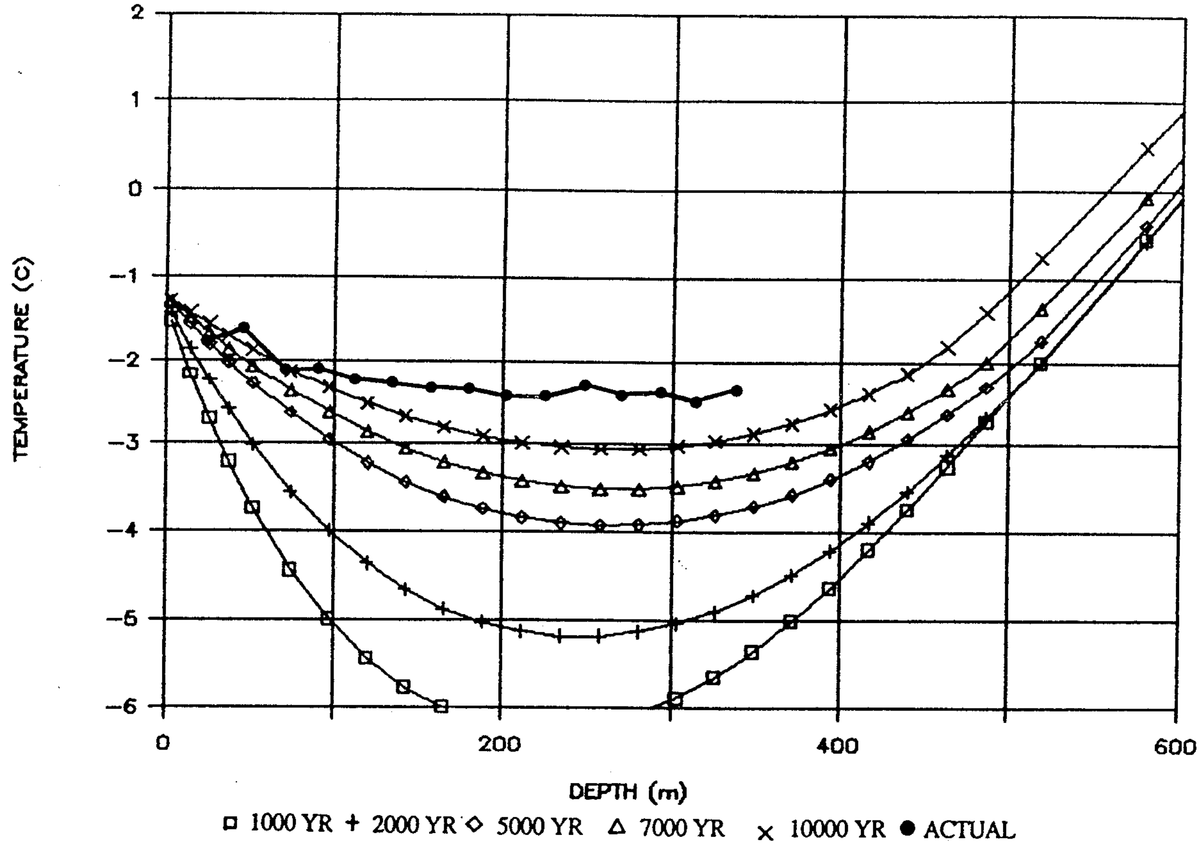


FIGURE C.6 AMA-6 UNIFORM SALINITY (10 ppt)

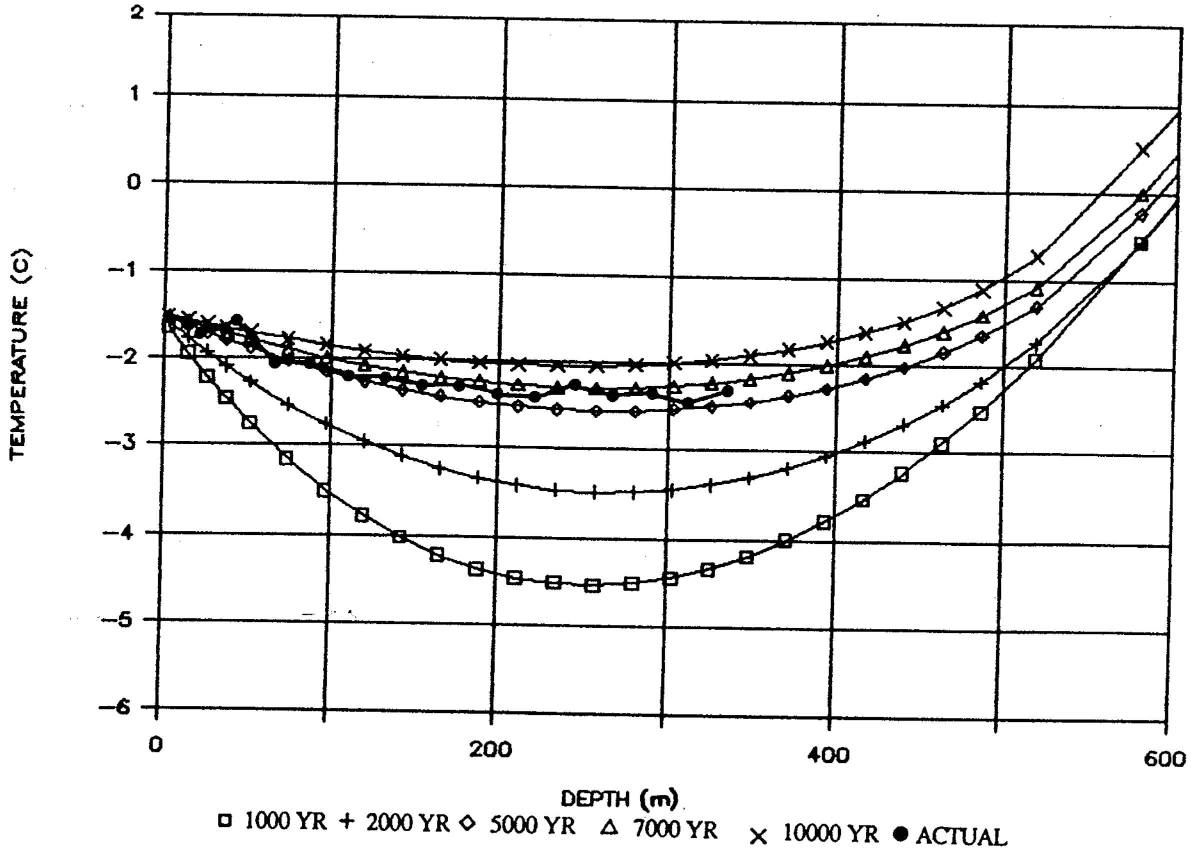


FIGURE C.7 AMA-1 6500 YEARS (Matched Run)

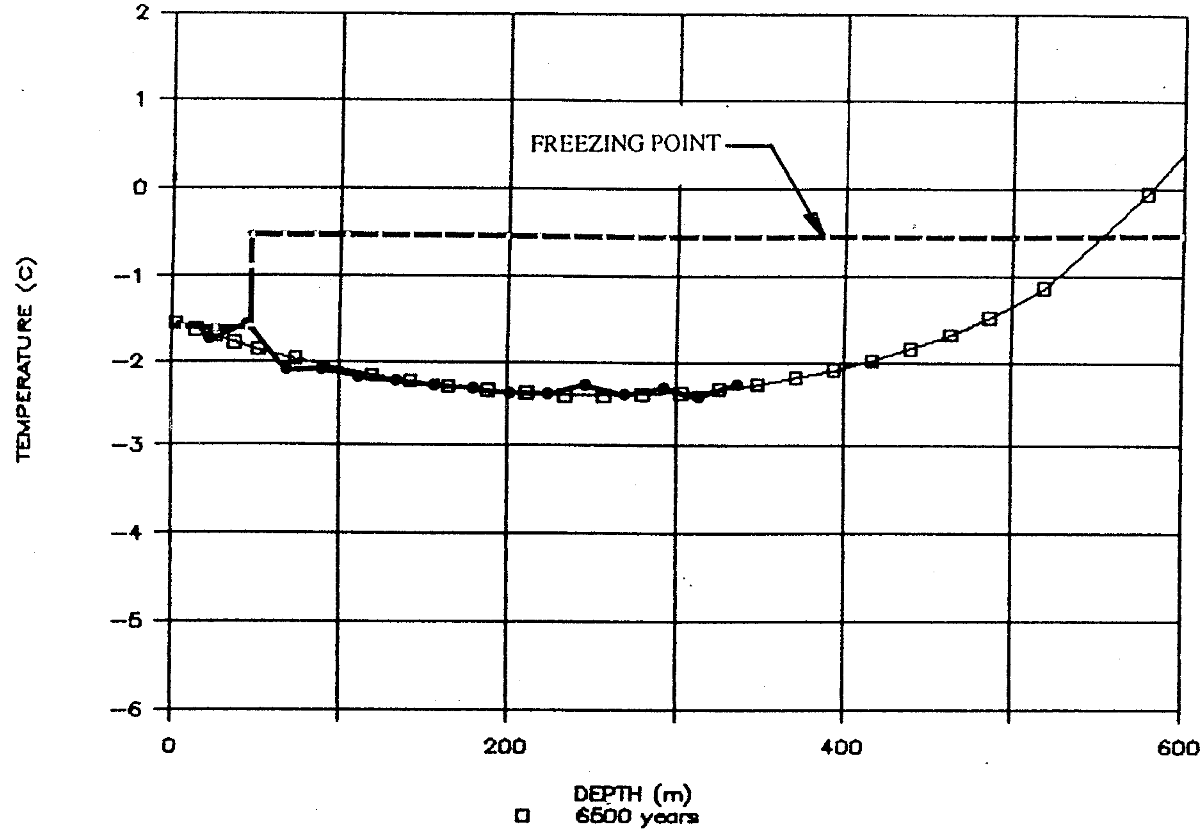


FIGURE C.8 AMA-3 5500 YEARS (Matched Run)

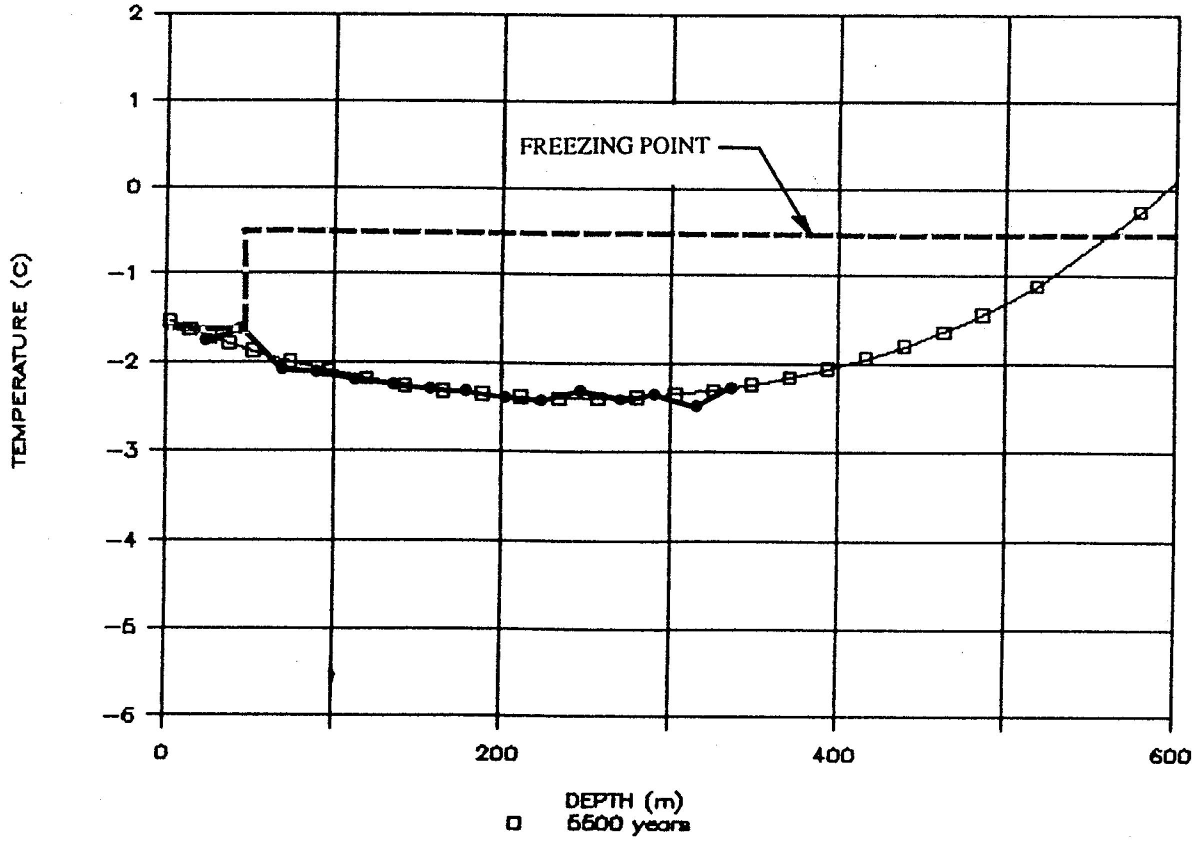


FIGURE C.9 AMA-4 7000 YEARS (Matched Run)

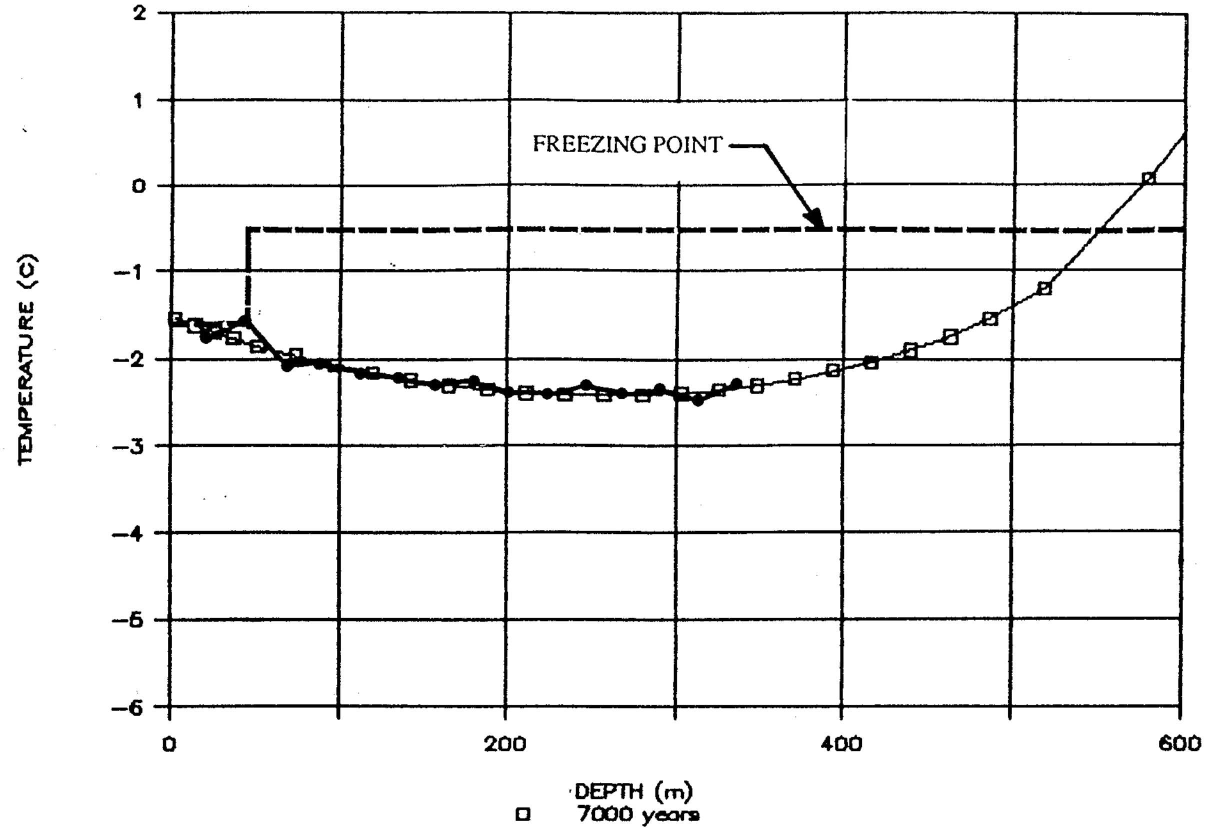


FIGURE C.10 AMA-6 6000 YEARS (Matched Run)

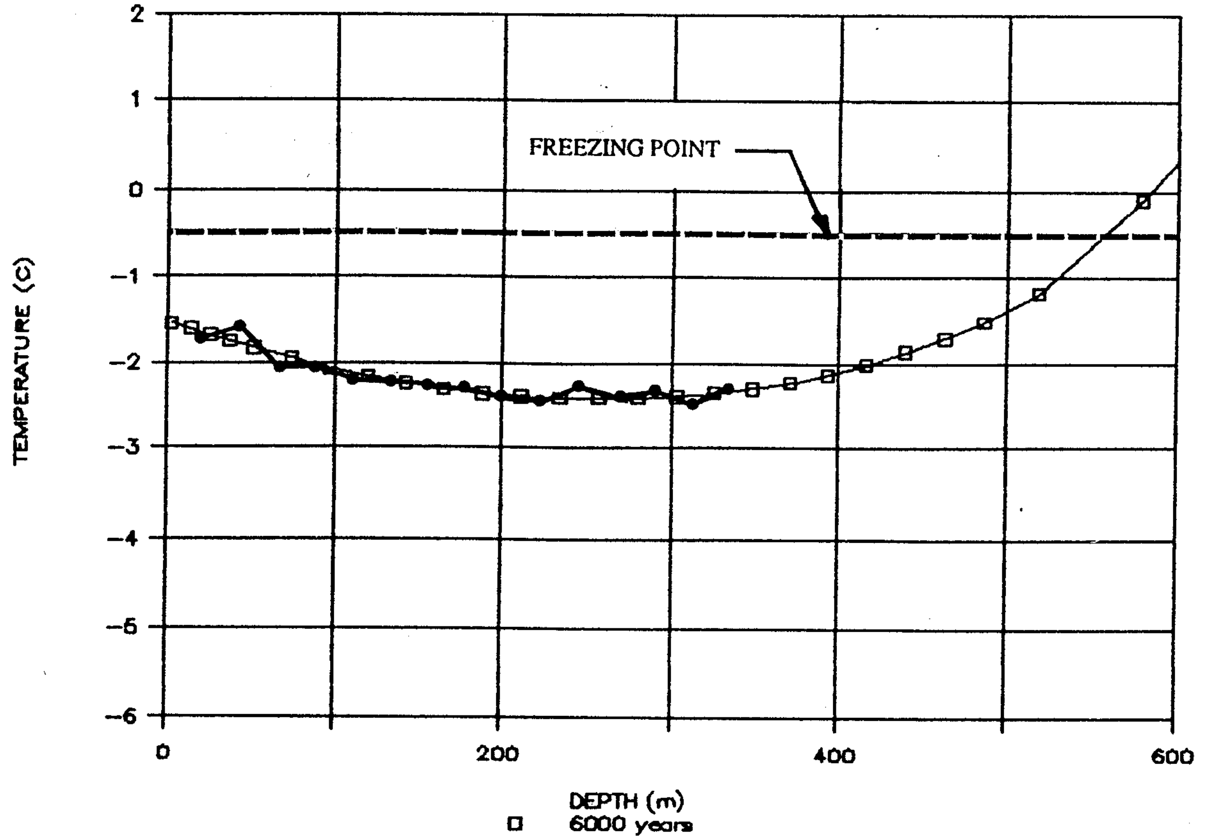


FIGURE C.11 AMA-7 Discrete Freezing Point

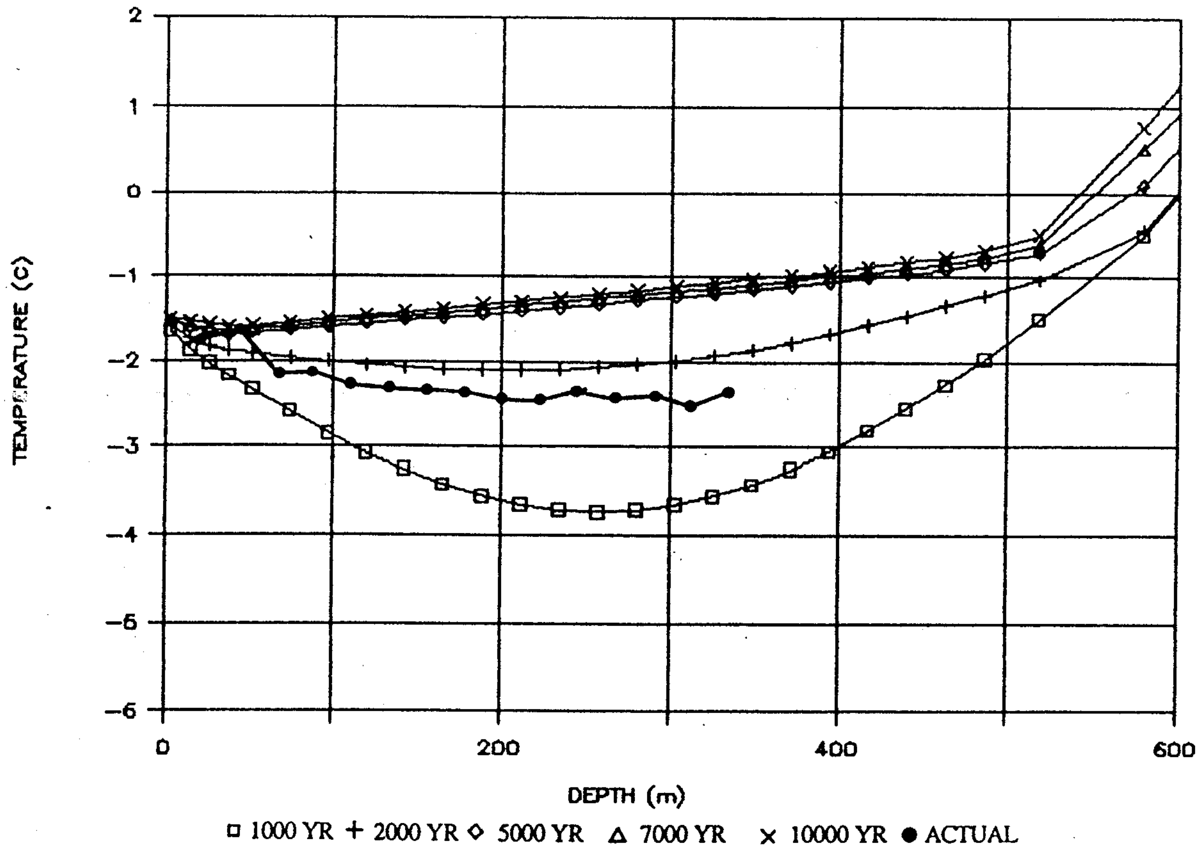


FIGURE C.12 AMA-7 1650 YEARS (Matched Run)