Environmental Studies No. 64

Permafrost and Terrain Research and Monitoring: Norman Wells Pipeline

Volume II
Research and Monitoring Results: 1983-1988

Canada

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Northern Affairs Program

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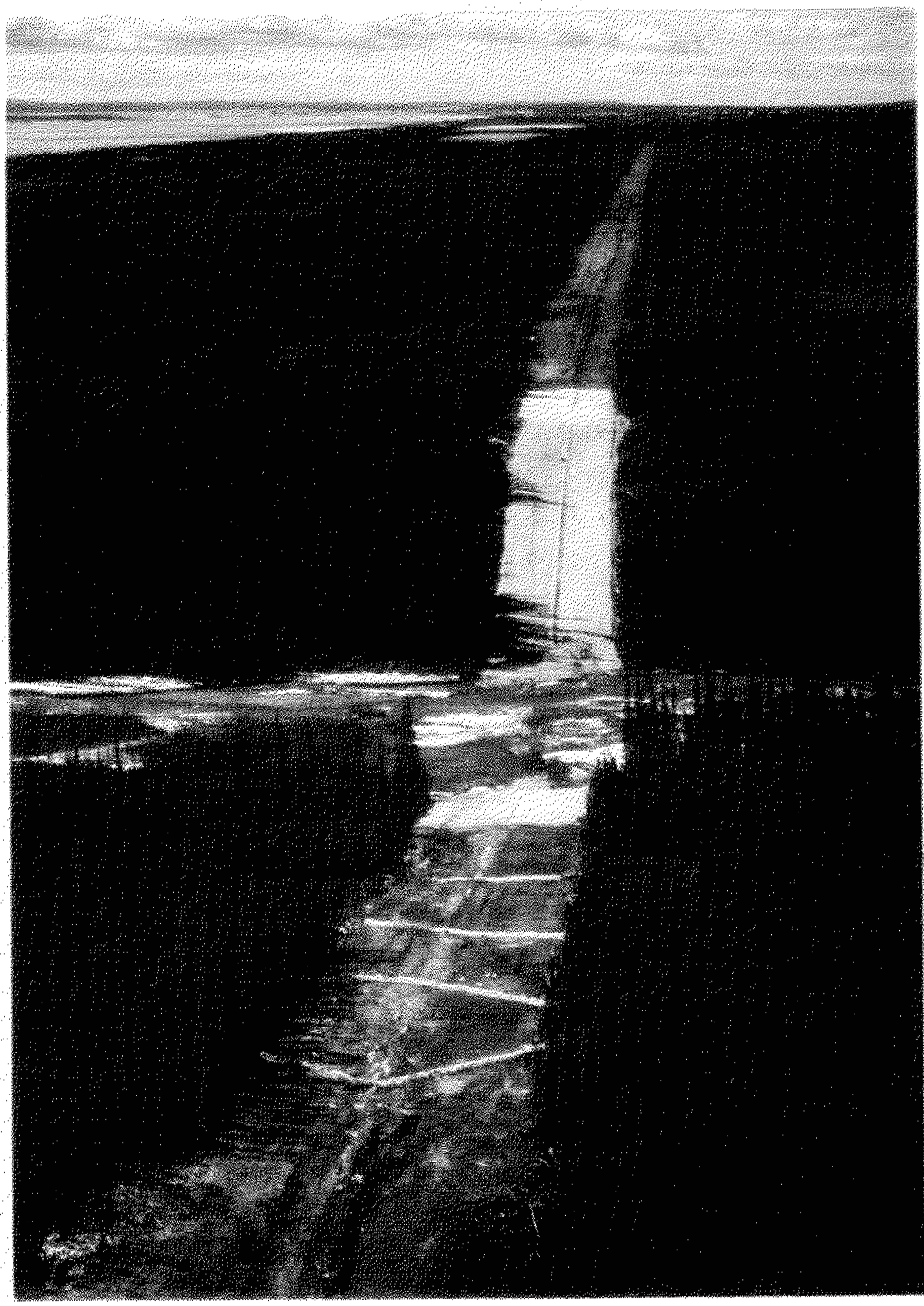

Norman Wells Pipeline crossing of Canyon Creek, 19 km south of Norman Wells. Norman Wells and the Mackenzie River are located in the upper center and left, respectively. The slope in the foreground is insulated with wood chips below the sandbag erosion control berms; the slope in the background is insulated and instrumented for monitoring (May 1985).

FOREWORD

This report on the Permafrost and Terrain Research and Monitoring Program along the Norman Wells Pipeline has been divided into two volumes. The first volume sets the stage by reviewing environmental and engineering considerations, and aspects of pipeline construction and operation. The second volume presents results from 1983 to 1988. Most important, the second volume contains conclusions and recommendations. The Executive Summary covers the contents of both volumes, as does the list of references. Abbreviations of names and technical terms and glossaries of permafrost and pipeline related terms also appear in both volumes.

For readers wanting more background on the instrumented monitoring sites along the pipeline, this information is contained in a site establishment report (Pilon et al., 1989) published as Geological Survey of Canada (Department of Energy, Mines and Resources) Open File 2044. Thermal data are available in a series of annual reports from the Geological Survey of Canada (Burgess, 1986 and 1987; Burgess and Naufal, 1989 and 1990. Open Files 86-6, 1621, 1987, 2155). A complete listing of reports and papers based on the Permafrost and Terrain Research and Monitoring Program is given in the appendix of each volume.

Copies of this Environmental Studies report (Volumes I and II) are available, without charge, by writing:

Public Enquiries and Response Division
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Please quote the complete title and departmental "QS" catalogue number (Permafrost and Terrain Research and Monitoring: Norman Wells Pipeline. Volume I - Environmental and Engineering Considerations. Volume II - Research and Monitoring Results: 1983-1988.)

The Geological Survey of Canada Open Files are available for viewing at all Geological Survey libraries and at the Resident Geologist's Office, Yellowknife. The Open Files can also be purchased from the following sales outlet:

Ashley Reproductions Inc.
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The site establishment report (Open File 2044) is also located in Territorial Government and Indian and Northern Affairs libraries in Yellowknife and the Science Institute of the Northwest Territories' library at the Inuvik Research Centre in Inuvik.

ACKNOWLEDGEMENTS

Many groups and individuals have given us invaluable help during field and office aspects of pipeline research and monitoring from 1983 to present. The scope of monitoring would have been impossible without this encouragement and help.

Interprovincial Pipe Line (NW) Ltd. has provided vital cooperation and support. Their assistance in establishing ground and pipe instrumentation in the Northwest Territories has made the extent of temperature measurement possible. This instrumentation has been the core of the monitoring since 1984. We extend special appreciation to W. Pearce, A. Pick, J. Smith, H. Sangster, D. Wishart, M. Yerichuk, W. Sartore, T. Kalnan, L. Riendeau, L. Cowie, D. Bruneau and M. Watt of IPL. We also wish to thank their consultants, W. Slusarchuk, A. Hanna, and M. Mitchell from Hardy BBT for their contributions in locating and establishing monitoring sites and the ongoing discussions of observations and design considerations.

The Land Resources Division and the Northern Affairs Program of INAC provide the essential financial support which is crucial to the Permafrost and Terrain Research and Monitoring program. The Northern Oil and Gas Action Program, the Arctic Land Use Research Program, the Pipeline Coordinator's Office, the Federal Panel on Energy Research and Development, the Office of Environmental Affairs (EMR), and the cooperating government departments (Energy, Mines and Resources Canada, National Research Council Canada and Agriculture Canada) have provided additional financial and other support.

We especially appreciate the support from INAC Regional Managers of Land Resources W. Dunlop and F. Adlem, Land's Office Manager Moie Edwardson, Chief Surveillance Officer B. Gauthier, and District Managers J. Umpherson and R. Cockney. Their contributions have influenced all aspects of the monitoring program. Special assistance in initiation and continuation of monitoring have come from S. Meldrum, J. Wallace, W. Stephen and V. Schilder. A. McRobert, D. Kearney and C. Coe have provided invaluable day to day assistance.

The key researchers involved in site selection, experimental design of thermal instrumentation, and site establishment are J. Pilon and A. Judge of Energy, Mines and Resources. Their advice and involvement, along with the capable technical expertise and assistance of V. Allen has been the basis of the main quantitative thermal data reported here. We also thank J. Naufal for her invaluable assistance in maintaining the data base available through EMR Open File reports.

Performance evaluation of wood chip insulated slopes has been aided by the work of J. Plunkett, H. Dahl, L. White and L. Goodrich of the National Research Council. We also recognize the extra contributions from L. McNeice, B. Fligg and P. Burns of the Regional Surveyor's Office, EMR, Yellowknife, in supervising site level surveys, and from R. Lanoville and R. Schmidt of the Territorial Forest Fire Centre, GNWT, Fort Smith, for providing summer precipitation data. We are indebted to C. Tarnocai, Agriculture Canada for sharing his expertise on northern soils and assisting with field observations.

We give very special recognition and appreciation to all those individuals listed in the Appendix of Volume II who have helped with field data collection, especially those who complete winter monitoring trips by snowmobile. D. Trudeau and D. Elliott have given outstanding help with field data collection. We would also like to thank J. Broadbent, L. Hill, D. Mulock, M. Brocklebank, C. Allen and F. Carmichael of Canadian Helicopters for safe transport and for additional help with field work.

The following persons reviewed drafts of all or parts of this report and offered comments which we greatly appreciate: T. Lawrence, A. Judge, B. Grey, B. Gauthier, J. Umpherson, and A. Pick. We accept responsibility, however, for the final statements and conclusions. We especially appreciate the assistance of Hugh Elliott and Wendy Duquette in the preparation of Volume II.

EXECUTIVE SUMMARY (Volumes I and II)

The 324 mm (12.7 in) diameter Norman Wells pipeline, owned and operated by Interprovincial Pipe Line (NW) Ltd. (IPL), is the first completely buried oil pipeline in the discontinuous permafrost zone in northern Canada. The 869 km (540 mi) long pipeline from Norman Wells, Northwest Territories to Zama, Alberta is located in thaw-sensitive terrain in a relatively remote part of northern Canada with limited seasonal access. Under a special Environmental Agreement the pipeline project is subject to the "principle of minimum practicable environmental and land use disturbance" for all aspects from planning to abandonment. Permafrost and terrain monitoring was established to evaluate impacts and identify improvements for this and future projects.

Major new approaches to the design and environmental impact mitigation have involved minimizing the length of pipeline in thaw-sensitive terrain, minimizing the energy input from the pipeline to ice-rich terrain (small pipe, initially chilled oil), locating the pipe in previously cleared terrain, retarding or preventing thaw of sensitive slopes (wood chip insulation), increasing the strength of the pipe (pipe grade, wall thickness), and frequent monitoring and rapid response to unstable conditions (drainage and erosion control problems).

Main pipeline construction was completed during the winters of 1983-1984 and 1984-1985. Pipeline operation started in April 1985. The pipeline has a design capacity of 4800 m^3/day (30,000 b/d) and an expected life of 25-30 years. The pipeline is buried at approximately 1 m depth and operates with three pump stations (km 0, km 336 and km 585). Oil movement from Norman Wells has increased from an average of 21,700 b/d in the first year of operation to 26,100 b/d in the third year.

The mechanism for a Permafrost and Terrain Research and Monitoring Program was established under the "Environmental Agreement" signed between IPL and the Minister of Indian and Northern Affairs Canada (INAC). The Company agreed to cooperate with the Minister in the development and implementation of a monitoring program. The monitoring program is designed to "facilitate an evaluation of the impact management process in order to improve on impact evaluation and mitigation on the Norman Wells Pipeline and future projects." Major aspects of the program include 1) examining thermal and terrain conditions at 23 main instrumented sites (e.g. pipe temperature sensors and a series of 5 and 20 m ground temperature cables on and off the right-of-way) over 819 km, 2) regular observations of overall right-of-way conditions, and 3) reviewing the performance of wood chip insulation used on thaw-sensitive slopes. Monitoring is planned for 5-10 years or until conditions stabilize.

The experience, observations and data bases available from the Permafrost and Terrain Research and Monitoring program are unique: similar data bases on an operational pipeline are not publicly available, for any other northern pipeline project in permafrost in North America or other circumpolar areas. The Program is also unique in being the first Canadian environmental monitoring program to address the issue of northern climate change in relation to environmental protection on a specific northern engineering project.

In terms of overall pipeline and environmental performance in N.W.T. through 1988, 1) there have been no pipeline breaks and few pipeline exposures and 2) effects extending beyond the right-of-way (ROW) have been localised and short term, primarily as a consequence of prompt IPL remedial action. Tension cracks and settlement on insulated slopes are regularly investigated. Since operations, two pipeline water crossings have been rebuilt (Hodgson Creek and Ochre River) and the pipe has been reburied in one floodplain (Hodgson Creek).

Volume I of this report summarizes environmental and engineering considerations related to Norman Wells pipeline design, construction and operation. Volume II presents results and recommendations based on observations and data obtained during construction and the first three to four years of operation. The results focus on the pipe temperature and ground temperature conditions, thaw depths, surface settlement, climate conditions, terrain performance, and thermal performance of wood chip insulated slopes. Some conclusions must be considered preliminary because of the short operational time of the pipeline and the variable time lag involved in detection of ground thermal and other changes, especially since the response of critical ice-rich permafrost terrain is slow.

CLIMATE

Climate data used in pipeline and mitigation design were based primarily on the records of two meteorological stations with more or less full records from 1951-1980 and two stations with incomplete records. These stations near the Mackenzie River only partially reflect diverse conditions along the pipeline corridor.

Climatic conditions, especially air temperature, winter snowcover, spring runoff and summer precipitation have played an important role in determining the terrain response to disturbance during the period 1983-1988. The climatic conditions are only partially known due to the limited meteorological data collection along the pipeline route: summer precipitation records have been significantly enhanced with the data obtained at Forestry stations near the pipeline since 1982.

Two major flood events have affected the Hodgson Creek crossing (km 305), in June 1986 and July 1988. In both cases, rainfall recorded at the nearby Mount Gaudet Forestry station reached or exceeded the estimated 100-year maximum 24-hour precipitation level. The July 1988 flood also eroded the river bank at Ochre River, exposing 20-30 m of pipeline which was undetected due to high silty water for about 2-3 weeks following the storm.

There is some evidence of a systematic climatic warming trend at Norman Wells and Fort Simpson, specifically warmer air temperatures over the last 40 years. Climate change, a concern raised in the environmental review of the project, was not specifically taken into consideration in the Norman Wells pipeline detailed thermal design (e.g. thaw depths, thaw settlement). IPL felt it could be addressed in terms of remedial response during operation.

PIPE AND GROUND TEMPERATURES

The pipe thermal regime follows an annual variation similar to that of the ground thermal regime (with the exception of the site adjacent to the Norman Wells pump station). At a particular point in time pipe temperature readings do however differ by more than 3-5 degrees from an adjacent ground temperature reading taken at a similar depth.

The short term thermal behaviour of the Norman Wells pipeline is that of a warm line, i.e. mean annual temperatures between 0°C and 5°C, both through the widespread discontinuous permafrost terrain in the northern part of the route (north of Wrigley) and the sporadic discontinuous permafrost terrain in the south. With the exception of warm (>2°C) winter pipe temperatures recorded at monitoring sites within 23 km downstream from Pump Station 3, observed pipe temperatures (monthly data) have been within the range of predicted values used in the detailed thermal design. An increase in pipe temperatures of 2-3 degrees occurs across Pump Station 3.

In general (18 of 23 instrumented sites between km 0 and 819) mean annual pipe temperatures increased during the first two years of pipeline operation, on average by 1 degree. This corresponds with an operations scenario of increased flow rate and increased chilling.

The warm mean annual pipe thermal regime (>0°C) indicates that frost heave due to development of a permanent frost bulb around the pipe is not of concern except near the chilled input.

Although the terrain and ground thermal regime may differ substantially between adjacent monitoring sites (within 1 km of each other), the pipe thermal regime remains the same. The distance required for the pipe to come into equilibrium with surrounding terrain is much greater than the scale of spatial variation in the ground thermal regime. In other words the pipe temperatures do not respond to short lengths of ground temperature change and either cool or warm the surrounding ground.

Mean annual pipe temperatures are generally warmer (on average by 1.5 degree) than mean annual ground temperatures on the ROW outside the trench area at a depth similar to that of initial pipeline burial (approximately 1 m) both in old and newly cleared right-of-way. Mean annual ground temperatures on-ROW are generally warmer than those off-ROW (by 1 degree on average). The warmer pipe temperatures are likely a combination of pipe effects and the more disturbed conditions in the trench as compared to the rest of the ROW.

The ground temperatures on the ROW also showed a general warming trend and continue to warm. The thermal response of ice-rich soils and thick frozen organic terrain is particularly slow due to freeze and thaw of pore water.

ACTIVE LAYERS AND THAW DEPTHS

The 30 year design thaw depth predictions varied from 6.1 to 12.2 m depending on terrain type and pipeline segment. Active layers, defined here by the maximum depth of penetration of the 0°C isotherm and measured by the ground temperature cables, ranged from <0.5 to <3.0 m on the ROW at the end of the 1987 thaw season. Active layers off-ROW by comparison were generally <1m. These observations are within the 30 year design thaw depth predictions; however short term thaw depth predictions have been reached at several sites and exceeded at one. By the fall of 1987, active layers on-ROW had increased by up to 1 m, while off-ROW they generally stayed the same.

SURFACE SETTLEMENT

Surface settlement affects surface drainage, ponding and erosion, and may be used as an indicator of possible pipe settlement (a pipe settlement monitoring program is undertaken separately by IPL).

For the ROW, excluding the pipe trench area, maximum recorded settlements of 50 cm or more have been observed at 6 sites. In the trench area, where settlement included thaw of frozen uncompacted backfill, the maximum recorded settlement to the end of the 1987 thaw season had reached 50 cm or more at 13 of the 23 instrumented sites, with 3 sites showing a maximum of 100 cm or more. Most of these sites have a depression in the ditch area below the level of the surrounding ground surface ("subsided ditchline").

Right-of-way surface settlement is ongoing. For the non-trench portion of the ROW localized areas of surface settlement in excess of the detailed design predictions have been observed at 4 sites. In the trench area surface settlement in excess of the design predictions has been recorded in localized pockets at 9 permafrost monitoring sites.

IPL has increased their pipe settlement monitoring since fall 1986 including the development of an "inertial monitoring pig" for the detection of differential pipe settlement and other pipe conditions.

WOOD CHIP INSULATION

An insulating cover of wood chips up to 1.8 m thick was placed on 55 thaw-sensitive slopes. The wood chips have exhibited internal heating as a result of microbial decomposition during the first summer period after placement. Except for about 6 slopes the warm temperatures (16 to 40°C) built up in the wood chip layers were dissipated with the coming of the cold fall air temperatures. Early snow cover provided an insulating layer which may have prevented heat removal from the other slopes. Some reheating occurred in most wood chip layers during the second summer period, but usually to a lesser extent.

The heating of some wood chip covered slopes, which were instrumented, has indicated thaw in excess of the 25-year predicted thaw. The evidence from snow melt patterns suggests that heating occurs in pockets within the wood chip layer and is not extensive on the slope.

Snow accumulation on the wood chip insulation, along with the conditions mentioned above, have combined to cause an increase in the mean annual ground temperature. This appears to be gradually thawing the soil beneath the wood chip layer. The influence of this thaw is more extensive throughout the wood chip covered slope surface than the localized microbial heating phenomenon.

TERRAIN PERFORMANCE

The most pronounced effect of construction disturbance on terrain has been the widespread subsidence of material along the ditchline. Ditch subsidence has presented a persistent erosion and maintenance problem but has been reduced through IPL's replacement of select backfill in the ditchline. IPL estimated, based upon interpretation of air photographs taken in July 1986, that approximately 30% of the ditch was visibly subsided. As general ROW surface subsidence continues there will be an increasing tendency for drainage to become channelled along the ROW and especially in the subsided ditch, both of which will be at lower levels than surrounding terrain.

In most cases erosion structures have performed well in limiting surface erosion of the ROW. However, numerous examples of small-scale erosion (gullying less than 10 cm deep) have occurred, frequently initiated by intense summer rain storms. A smaller number of erosion events have resulted in gullying to depths ranging from 20 cm to 3-4 m, in some cases resulting in loss of ditch backfill and exposure of the pipe. There has also been complete or partial failure of drainage control structures (e.g. Great Bear River north slope, Blackwater River north slope). Erosion has also occurred in areas where no drainage control structures were included in the original design (e.g. south side of Norman Range).

At several water crossings erosion, and associated disturbance of mitigation structures, has occurred due to high water events (e.g. Hodgson Creek, Ochre River and others) and, in some cases, insufficient streambank protection (e.g. Canyon Creek, Heleva Creek and others). Major floods affecting Hodgson Creek (1986, 1988) and Ochre River (1988) pipeline crossings have illustrated the difficulty in predicting hydrologic regimes within the Mackenzie Valley, and argue for a more conservative approach to flood estimation.

IMPROVEMENTS

Improvements made in mitigation through fall 1988 as a consequence of discussions and review of observations and data from the Permafrost and Terrain Research and Monitoring Program and the Company's own monitoring program include: 1) changes related to operating oil temperatures, 2) review of data and initiation of remedial activity related to wood chip insulation of thaw-sensitive slopes, 3) review of rate of thaw settlement and use of surface changes to indicate when thaw settlement might be affecting conditions below the pipe, 4) more timely exchange of summer precipitation data from storm events in remote locations along the pipeline, and 5) remedial measures implemented by IPL as a result of notification from observers on the Research and Monitoring Program.

Improvements made in impact evaluation include: 1) refining parameters examined, 2) testing and utilizing various automatic and manual recording and handling systems, and 3) evaluating frequency and timing of monitoring measurements.

RECOMMENDATIONS

A total of 38 recommendations are given. The majority of the these involve improvements to impact mitigation and environmental protection related to project planning, operations and maintenance. Numerous recommendations emphasize the need for continued data collection, especially to evaluate mitigation in ice-rich permafrost and the potential effects of climate change (temperature and precipitation). The following are some of the major recommendations.

1. It is recommended that INAC continue permafrost and terrain research and monitoring until conditions stabilize (e.g. little evidence of erosion and settlement, or slope, stream bank and thermal instability), or until it is felt that no further practical lessons leading to improvements on the Norman Wells Pipeline or future projects are likely to be learned.

2. It is recommended that government and industry implement cooperative research and monitoring programs on other northern projects in permafrost terrain, where evaluation might lead to improvements in mitigation, and improve on the capability to anticipate environmental problems.

3. To assist in both the planning and safe operation of future pipelines and the continued maintenance of the Norman Wells pipeline, increased attention should be focused upon the implications of climate change. Emphasis should be placed upon analysis of climatic trends and variability, as well as on mean conditions. Rapid climatic change may limit the validity of using 30-year normals values as inputs in geotechnical and geothermal models and environmental protection plans.

4. It is recommended that observations address 1) the complexities and mechanisms of pipe-ground heat exchange (particularly in wet trench conditions where water movement and hence convective heat transfer may occur), and 2) the effects of changes in the pipe thermal regime on the thermal

performance, and hence stability of insulated thaw-sensitive slopes.

5. It is recommended that the use of wood chips to reduce thaw of permafrost on future projects consider methods to: 1) keep the wood chips dry throughout the year, and 2) restrict air entering the wood chip layer.

6. It is recommended that water crossings be designed for a maximum flood based on geological/geomorphic evidence, hydrological models, and considerations based on climate change scenarios.

7. It is recommended that the ROW be monitored and maintained frequently (weekly or more often for this and future northern pipelines, especially during the first few years following construction), particularly after spring snowmelt runoff and major summer storm events. Possible misplacement of berms, omission of watercourses from the design, and reduced vegetation cover renders the ROW surface particularly vulnerable to erosion during this period.

RÉSUMÉ (volumes I et II)

Le pipeline de Norman Wells dont le diamètre est de 324 mm (12,7 po) appartient à la société Interprovincial Pipeline (NW) Ltd. (IPL) qui en assure l'exploitation; dans la zone de pergélisol discontinu du Nord canadien, il s'agit du premier oléoduc entièrement enfoui. Le pipeline de 869 km (540 mi) de longueur à partir de Norman Wells (Territoires du Nord-Ouest) jusqu'à Zama (Alberta) est situé en terrain sensible au dégel dans une région relativement isolée du Nord canadien à laquelle l'accès est limité à certaines périodes de l'année. En vertu d'une entente spéciale sur l'environnement, le projet de pipeline est soumis au "principe de perturbation minimale possible de l'environnement et de l'utilisation du terrain" pour tous les aspects qui vont de la planification du projet à l'abandon des lieux. L'observation du pergélisol et du terrain a été entreprise afin d'évaluer les impacts et d'identifier les améliorations dans ce projet et les autres à venir.

Les principales nouvelles approches à la conception du pipeline et à l'atténuation de l'impact sur l'environnement ont consisté à minimiser la longueur du pipeline en terrain sensible au dégel, à minimiser le transfert d'énergie du pipeline au terrain à haute teneur en glace (petite conduite, pétrole initialement refroidi), à situer la conduite dans des terrains antérieurement dégagés, à retarder ou à empêcher le dégel des talus sensibles (isolation aux copeaux de bois), à augmenter la résistance de la conduite (qualité de la conduite, épaisseur de la paroi), à observer fréquemment et à réagir rapidement aux conditions instables (problèmes de drainage et lutte contre l'érosion).

La construction principale du pipeline a été terminée au cours des hivers 1983-1984 et 1984-1985. L'exploitation du pipeline a commencé en avril 1985. Le pipeline possède un débit d'apport maximal de 4800 m^3/jour (30 000 b/j) et une durée de vie prévue de 25-30 ans. Le pipeline est enfoui à une profondeur d'environ 1 m et est exploité à l'aide de trois stations de pompage (km 0, km 336 et km 585). L'acheminement du pétrole à partir de Norman Wells est passé d'une moyenne de 21 700 b/j au cours de la première année d'exploitation à 26 100 b/j la troisième année.

Le mécanisme de création d'un programme de recherche et d'observation du pergélisol et du terrain a été établi dans le cadre de l'entente sur l'environnement signée entre IPL et le ministre des Affaires indiennes et du Nord Canada (MAINC). La société a convenu de collaborer avec le ministre pour l'élaboration et la mise en oeuvre d'un programme d'observation. Ce programme est conçu pour "faciliter l'évaluation du processus de gestion des

impacts afin d'améliorer l'évaluation et l'atténuation des impacts sur l'oléoduc de Norman Wells et les projets à venir". Les principaux aspects du programme sont les suivants : 1) examen des conditions thermiques et de terrain sur 23 principaux sites munis d'appareils de mesure (p. ex. capteurs de température de la conduite et une série de câbles de 5 et 20 m de longueur pour mesurer la température du sol tantôt sur le droit de passage, tantôt en dehors de celui-ci) sur une distance de 819 km, 2) observations régulières des conditions générales du droit de passage et 3) examen du comportement de l'isolation aux copeaux de bois employée sur les talus sensibles au dégel. L'observation est planifiée sur une période de 5-10 ans ou jusqu'à ce que les conditions se stabilisent.

L'expérience, les observations et les bases de données accessibles grâce au programme d'observation et de recherche sur le pergélisol et le terrain sont uniques : des bases de données semblables sur un pipeline en service ne sont pas accessibles au public, pour n'importe quel autre projet de pipeline nordique en milieu pergélisolé d'Amérique du Nord ou dans toute autre région circumpolaire. Le programme est aussi unique en ce qu'il est le premier programme canadien d'observation de l'environnement à porter sur le problème de changement climatique nordique en relation avec la protection de l'environnement sur un projet spécifique d'ingénierie nordique.

Du point de vue du comportement général du pipeline et de l'environnement dans les T.N.-O. de 1983 à 1988, 1) il n'y a eu aucune rupture de pipeline et seulement quelques sections de pipeline se sont retrouvées exposées, et 2) les effets produits au-delà du droit de passage ont été localisés et corrigés dans de courts délais, principalement par suite d'une action rapide d'IPL. Les fissures dues à la contrainte et le tassement sur les talus isolés font l'objet d'études régulières. Depuis le début de l'exploitation, deux traverses de pipeline au fond de l'eau ont été reconstruites (ruisseau Hodgson et rivière Ochre) et la conduite a été réenfouie dans une plaine d'inondation (ruisseau Hodgson).

Le volume I du présent rapport dresse un bilan des considérations environnementales et techniques liées à la conception du pipeline de Norman Wells, ainsi qu'à sa construction et à son exploitation. Le volume II présente les résultats et les recommandations basées sur les observations et les données obtenues pendant la construction ainsi que pendant les trois ou quatre premières années d'exploitation. Les résultats portent essentiellement sur les conditions thermiques de la conduite et du sol, sur les profondeurs de dégel, sur le tassement en surface, sur les conditions climatiques, sur le comportement du terrain et le comportement thermique des talus isolés aux copeaux de bois.

Certaines conclusions doivent être envisagées au préalable en raison de la courte période d'exploitation du pipeline et du retard variable accusé dans la détection des changements thermiques du sol et autres, spécialement parce que lente est la réaction du terrain pergélisolé à haute teneur en glace.

CLIMAT

Les données climatiques employées dans la conception du pipeline et de l'atténuation de l'impact sur l'environnement ont été basées principalement sur les archives de deux stations météorologiques possédant des archives plus ou moins complètes pour la période 1951-1980 ainsi que de deux stations dont les archives sont incomplètes. Ces stations situées près du fleuve Mackenzie ne reflètent que partiellement les diverses conditions qui règnent dans le corridor du pipeline.

Les conditions climatiques, spécialement la température de l'air, le manteau nival d'hiver, le ruissellement printanier et les précipitations estivales ont joué un rôle important dans la détermination de la réaction du terrain aux perturbations pendant la période 1983-1988. Les conditions climatiques ne sont connues que partiellement parce que la collecte des données météorologiques est limitée le long du tracé du pipeline : les enregistrements de précipitations estivales ont été sensiblement rehaussés avec les données obtenues auprès des stations de foresterie situées à proximité du pipeline depuis 1982.

Deux grandes inondations ont affecté la traverse du ruisseau Hodgson (km 305), en juin 1986 et en juillet 1988. Dans les deux cas, les pluies enregistrées à la station forestière voisine de Mount Gaudet ont atteint ou dépassé le niveau de précipitation maximal de 24 heures estimé sur une période de 100 ans. L'inondation de juillet 1988 a aussi érodé la rive sud de la rivière Ochre, exposant 20-30 m de pipeline, ce qui est passé inaperçu en raison de la forte turbidité de l'eau pendant les 2 ou 3 semaines qui ont suivi la tempête.

Il existe quelques preuves de tendance à un réchauffement systématique du climat à Norman Wells et à Fort Simpson, la température de l'air s'étant particulièrement réchauffée au cours des 40 dernières années. Le changement climatique, un facteur soulevé dans l'examen environnemental du projet, n'a pas été spécifiquement pris en compte dans la conception thermique détaillée du pipeline de Norman Wells (p. ex. profondeurs de dégel, tassement dû au dégel), IPL a estimé qu'elle pouvait aborder cette question en appliquant des mesures correctives au cours de l'exploitation.

TEMPÉRATURE DE LA CONDUITE ET DU SOL

Le régime thermique de la conduite obéit à une variation annuelle analogue à celle du régime thermique du sol (à l'exception du site adjacent à la station de pompage de Norman Wells). À un moment donné, les lectures de température de la conduite diffèrent toutefois de plus de 3 à 5 degrés d'une lecture de température du sol prise dans le voisinage à une profondeur comparable.

Le comportement thermique à court terme du pipeline de Norman Wells est celui d'un oléoduc chaud (c'est-à-dire des températures annuelles moyennes supérieures à 0°C et entre 0 C et 5 C), tout au long de son traject à travers le terrain à pergélisol discontinu répandu dans la partie nord du tracé (au nord de Wrigley) ainsi qu'à travers le pergélisol discontinu sporadique dans le sud. À l'exception des chaudes températures (> 2 C) de conduite enregistrées dans les sites d'observation situés dans un rayon de 23 km en aval de la station de pompage n 3, les températures de conduite observées (données mensuelles) se sont situées à l'intérieur de l'intervalle des valeurs prédites employées dans la conception thermique détaillée. Une augmentation des températures de conduite de 2 ou 3 degrés se produit à travers la station de pompage n 3.

De manière générale (18 des 23 sites munis d'appareils entre les km 0 et 819), les températures de conduite annuelles moyennes ont augmenté pendant les deux premières années d'exploitation du pipeline, en moyenne de 1 degré. Cela correspond à un scénario d'exploitation à débit accru et à refroidissement accru.

Le régime thermique annuel moyen chaud des conduites (> 0 C) indique que le soulèvement dû au gel dû à la formation d'un bulbe de gel permanent autour de la conduite n'est pas inquiétant sauf à proximité de l'apport refroidi.

Bien que le terrain et le régime thermique du sol puissent différés considérablement entre des sites d'observation voisins (à moins de 1 km l'un de l'autre), le régime thermique de la conduite reste le même. La distance requise pour que la conduite viennent en équilibre avec le terrain avoisinant est beaucoup plus grande que l'échelle de variation spatiale qui existe dans le régime thermique du sol. En d'autres mots, les températures de conduite ne réagissent pas aux courtes étendues de terrain avec un changement de la température du sol et elles refroidissent ou réchauffent le sol qui les entoure.

Les températures de conduite annuelles moyennes sont généralement plus chaudes (en moyenne de 1,5 degré) que les températures du sol annuelles moyennes sur le droit de passage à l'extérieur de la zone de tranchée à une profondeur comparable à celle de l'enfouissement initial du pipeline (environ 1 m), tant dans un droit de passage anciennement dégagé que dans un droit de passage nouvellement dégagé. Les températures du sol annuelles moyennes sur le droit de passage sont généralement plus chaudes que celles en dehors de celui-ci (de 1 degré en moyenne). Les températures de conduite plus chaudes sont vraisemblablement le résultat d'une combinaison des effets de conduite et des conditions plus perturbées dans la tranchée comparativement au reste du droit de passage.

Les températures du sol sur le droit de passage ont aussi montré une tendance au réchauffement général et continuent à se réchauffer. La réaction thermique des sols à haute teneur en glace et du terrain organique gelé sur une forte épaisseur est particulièrement lente en raison du gel et du dégel de l'eau interstitielle.

MOLLISOLS ET PROFONDEURS DE DÉGEL

Les prédictions de profondeur de dégel calculées sur 30 ans ont varié de 6,1 à 12,2 m suivant le type de terrain et la zone de construction. Les mollisols, définis ici par la profondeur maximale de pénétration de l'isotherme 0 C et mesurés à l'aide de câbles de température dans le sol, ont oscillé entre < 0,5 à < 3,0 m sur le droit de passage à la fin de la période de dégel de 1987.

À titre de comparaison, les mollisols situés en dehors du droit de passage étaient généralement < 1 m. Ces observations se situent à l'intérieur des prédictions sur la profondeur de dégel calculée sur 30 ans; des profondeurs de dégel prédites à court terme ont toutefois été atteintes dans quelques sites et elles ont été dépassées à un endroit. À l'automne de 1987, les mollisols mesurés sur le droit de passage ont connu des augmentations atteignant 1 m, tandis que ceux mesurés en dehors du droit de passage sont généralement demeurés les mêmes.

TASSEMENT DE SURFACE

Le tassement de surface affecte le drainage, la formation d'étangs et l'érosion en surface, et peut être utilisé comme indicateur d'un affaisement possible de la conduite (un programme d'observation de l'affaisement de la conduite est entrepris séparément par IPL).

Pour le droit de passage, à l'exclusion de la zone de tranchée de la conduite, des tassements ayant enregistré un maximum de 50 cm ou plus ont été observés dans six sites. Dans la zone de tranchée, où le tassement comprenait le dégel du remblai gelé sans compaction, le tassement maximal enregistré à la fin de la période de dégel de 1987 avait atteint 50 cm ou plus dans 13 des 23 sites d'observations, dont trois montrant un maximum de 100 cm ou plus. La plupart de ces sites possèdent une dépression dans la zone de fossé sous le niveau de la surface du sol environnant ("ligne de fossé affaissée").

Le tassement de surface du droit de passage se poursuit. Sur le droit de passage à l'extérieur de la zone de tranchée, des zones localisées de tassement de surface dépassant les valeurs détaillées des prédictions ont été observées dans quatre sites. Dans la zone en tranchée, le tassement de surface dépassant les prédictions calculées a été enregistré dans quelques poches localisées à neuf sites d'observation du pergélisol.

IPL a intensifié son observation de l'affaisement de la conduite depuis l'automne 1986 en y ajoutant la mise au point d'un "furet de surveillance inertielle" pour la détection des mouvements différentiels de la conduite et ainsi que d'autres conditions de la conduite.

ISOLATION AUX COPEAUX DE BOIS

Une couverture isolante faite de copeaux de bois et pouvant atteindre 1,8 m d'épaisseur a été placée sur 55 talus sensibles au dégel. Les copeaux de bois ont montré des signes de chauffage interne par suite de la décomposition microbienne qui s'est produite pendant le premier été après leur mise en place. Sauf dans le cas d'environ six talus, les températures chaudes (16-40 C) enregistrées dans les couches de copeaux de bois ont été dissipées avec l'arrivée des températures froides de l'air d'automne. Le manteau nival hâtif a fourni une couche isolante ayant pu empêcher le soutirement de chaleur aux autres talus. Un certain réchauffement s'est produit dans la plupart des couches de copeaux de bois pendant le deuxième été, mais habituellement dans une moindre mesure.

Le réchauffement de certains talus recouverts de copeaux de bois et équipés de câbles de température a indiqué un dégel dépassant le dégel prédit sur 25 ans. La configuration de fonte des neiges suggère que le réchauffement se limite à des poches situées à l'intérieur de la couche de copeaux de bois et que ce réchauffement n'est pas extensif sur le talus.

L'accumulation de neige sur la couche isolante de copeaux de bois, de même que les conditions susmentionnées, se sont combinées pour provoquer une hausse de la température annuelle moyenne du sol. Cela semble faire progressivement dégeler le sol situé au-dessous de la couche de copeaux de bois. L'influence de ce dégel est plus poussée à travers la surface du talus recouvert de copeaux de bois que le phénomène de réchauffement microbien localisé.

COMPORTEMENT DU TERRAIN

L'effet le plus marqué de la perturbation due à la construction sur le terrain a été l'affaissement généralisé des matériaux situés le long de la ligne de fossé. L'affaissement du fossé a présenté un problème persistant d'érosion et de maintenance, mais il a été réduit grâce à l'intervention d'IPL qui a placé un remblai choisi dans la ligne de fossé. IPL a estimé, en se basant sur l'interprétation de photographies aériennes prises en juillet 1986, qu'environ 30 % du fossé était visiblement affaissé. Comme l'affaissement général de la surface du droit de passage se poursuit, le drainage aura de plus en plus tendance à se canaliser le long du droit de passage et particulièrement dans le fossé affaissé, puisque tous deux se trouveront à des niveaux plus bas que le terrain avoisinant.

Dans la plupart des cas, les ouvrages de protection contre l'érosion se sont bien comporté en limitant l'érosion de la surface. Souvent à la suite de fortes tempêtes de pluie survenues en été, de nombreux cas d'érosion à petite échelle (ravinement de profondeur inférieure à 10 cm) ont eu lieu. Des cas d'érosion moins nombreux ont produit un ravinement à des profondeurs comprises entre 20 cm et 3-4 m, allant même jusqu'à produire dans certains cas des pertes de remblai du fossé et la mise à nu de la conduite. Il y a aussi eu des cas de rupture complète ou partielle des ouvrages de régularisation du drainage (p. ex. le talus nord de la Grande rivière de l'Ours, le talus nord de la rivière Black Water). L'érosion a aussi affecté des zones où la conception originale avait indiqué que des d'ouvrages de régularisation du drainage n'étaient pas requises (p. ex. côté sud du chaînon Norman).

À plusieurs points de franchissement de cours d'eau, l'érosion et la perturbation connexes des ouvrages de réduction, ont été causées par les hautes eaux (p. ex. ruisseau Hogson, ruisseau Ochre et autres) et, dans certains cas, une protection insuffisante des rives (p. ex. ruisseau Canyon, ruisseau Heleva et autres). Les grandes inondations ayant affecté les traversées du ruisseau Hodgson (1986, 1988) et de la rivière Ochre (1988) ont illustré la difficulté de prédire les régimes hydrologiques dans la vallée du Mackenzie et justifient une approche plus conservatrice en matière d'estimation des crues.

AMÉLIORATIONS

Les améliorations apportées à l'atténuation des impacts sur l'environnement, pendant la période allant de 1983 à l'automne 1988, par suite des discussions et de l'examen des observations et des données provenant du programme d'observation et de recherche du pergélisol et du terrain ainsi que du programme d'observation exécuté par la société IPL même comprennent ce qui suit : 1) des changements relatifs aux températures du pétrole pendant l'exploitation du pipeline, 2) l'examen des données et l'amorce de mesures correctrices liées à l'isolation aux copeaux de bois des talus sensibles au dégel, 3) l'examen de la vitesse du tassement dû au dégel et le recours à des changements de surface pour indiquer les moments où le tassement dû au dégel pourrait affecter les conditions régnant sous la conduite, 4) échange opportun des données de précipitation estivale provenant des tempêtes survenues à des endroits isolés le long du pipeline et 5) la mise en oeuvre par IPL de mesures correctrices par suite d'avis exprimés par des observateurs faisant partie du programme de recherche et d'observation.

Les améliorations apportées à l'évaluation des impacts sont les suivantes : 1) le raffinement des paramètres examinés, 2) l'essai et l'utilisation de divers systèmes automatiques et manuels d'enregistrement et de manipulation, et 3) l'évaluation de la fréquence et de la chronicité des mesures effectuées pendant l'observation.

RECOMMANDATIONS

En tout, 38 recommandations ont été faites. La majorité d'entre elles prévoient des améliorations à l'atténuation des impacts et à la protection environnementale relatives à la planification des travaux, à l'exploitation et à la maintenance. De nombreuses recommandations insistent sur la nécessité de collecter des données de façon suivie, particulièrement afin d'évaluer les méthodes d'atténuation dans le terrain pergélisolé à haute teneur en glace et les effets potentiels du changement de climat (température et précipitations). Certaines des principales recommandations sont les suivantes.

1. Il est recommandé que MAINC poursuive les recherches et l'observation du pergélisol et du terrain jusqu'à ce que les conditions se stabilisent (p. ex. rarification des cas d'érosion et de tassement, ou d'instabilité des talus, des rives de cours d'eau, et d'instabilité thermique), ou jusqu'à ce que l'on estime qu'il n'y a plus de leçons pratiques à tirer de la situation pour apporter des améliorations aux pipelines de Norman Wells ou à d'autres futurs projets semblables.

2. Il est recommandé que le gouvernement et l'industrie mettent en oeuvre des programmes coopératifs de recherche et d'observation portant sur d'autres projets nordiques en milieu pergélisolé, dans lesquels une évaluation pourrait conduire à des améliorations de l'atténuation des impacts ainsi qu'à l'amélioration de la capacité d'anticiper les problèmes environnementaux.

3. Pour faciliter à la fois la planification et l'exploitation en toute sécurité des futurs pipelines ainsi que la maintenance suivie du pipeline de Norman Wells, une attention accrue devrait être apportée aux implications du changement climatique. L'accent devrait être mis sur l'analyse des tendances climatiques et de la variabilité du climat, de même que sur les conditions moyennes. Un changement climatique rapide peut limiter la validité des normales établies sur 30 ans en tant que paramètres de modèles géotechniques et géothermiques ainsi que de plans de protection de l'environnement.

4. Il est recommandé que les observations portent sur les points suivants : 1) la complexité et les mécanismes d'échange thermique entre la conduite et le sol (particulièrement dans des conditions de tranchées humides où le mouvement de l'eau,

et partant, une transmission de chaleur par convection peut se produire) et 2) les effets des changements dans le régime thermique de la conduite sur le rendement thermique et, de ce fait, la stabilité des talus sensibles au dégel quand ils sont isolés.

5. Il est recommandé que l'emploi des copeaux de bois pour réduire le dégel du pergélisol dans les projets à venir tienne compte de méthodes pour : 1) garder sec les copeaux de bois pendant toute l'année et 2) restreindre la quantité d'air pénétrant dans la couche de copeaux de bois.

6. Il est recommandé que les points de franchissement des cours d'eau soient conçus en fonction des crues maximales en s'appuyant sur les connaissances géologiques et géomorphologiques, des modèles hydrologiques et des considérations basées sur des scénarios de changement climatique.

7. Il est recommandé que le droit de passage fasse l'objet d'une observation suivie et d'un entretien fréquent (hebdomadaire ou même plus souvent dans le cas du pipeline actuel et de futurs pipelines nordiques, spécialement pendant les premières années suivant leur construction), particulièrement après la période de ruissellement des eaux de fonte des neiges au printemps et les grandes tempêtes d'été. L'aménagement possible de bermes au mauvais endroit, l'omission des cours d'eau dans les calculs et une couverture végétale réduite rendent la surface du droit de passage particulièrement vulnérable à l'érosion pendant cette période.

TABLE OF CONTENTS (VOLUMES I AND II)

VOLUME I - ENVIRONMENTAL AND ENGINEERING CONSIDERATIONS

VOLUME II - RESEARCH AND MONITORING RESULTS: 1983-1988

LIST OF TABLES

VOLUME II

LIST OF FIGURES

VOLUME II

Abbreviations

(A number of abbreviations have been used for names and technical terms during the project review, research and monitoring, and subsequent reporting. For clarification we have listed abbreviations below.)

For Names

AG-CAN	Agriculture Canada
AES	Atmospheric Environment Service (Environment Canada)
CNT	Canadian National Telecommunications
CSA	Canada Standards Association
DIAND name)	Department of Indian Affairs and Northern Development (legal see INAC
EARP	Environmental Assessment and Review Process
EIS	Environmental Impact Statement
EMR	Energy, Mines and Resources
EPP	Environmental Protection Plan
ESSO	Esso Resources Canada Ltd.
FEARO	Federal Environmental Assessment and Review Office
GNWT	Government of the Northwest Territories
GSC	Geological Survey of Canada
INAC	Indian and Northern Affairs Canada (current reference to DIAND except in legal documents)
IPL	Interprovincial Pipe Line Limited or Interprovincial Pipe Line (NW) Limited
NEB	National Energy Board
NRC	National Research Council
N.W.T.	Northwest Territories (also NWT)
OC-35 (NEB)	Certificate of Public Convenience and Necessity No. OC-35
PCC	Project Co-ordinating Committee
PTRM	Permafrost and Terrain Research and Monitoring
ROW	Right-of-way (Also R.O.W.)

For Technical Terms

b/d	barrels/day
°C	degrees Celsius (generally used unit for absolute temperatures)
gm/cc	grams per cubic centimetre
ha	hectare (1 ha = 100 m x 100 m)
K	degrees Kelvin (= Celsius degree, generally used unit for relative change in temperature)
km	kilometre
Kmp	kilometre post (also kp) location along pipeline
kPa	kilopascal (SI unit of measurement for pressure)
m	metre; m^3 = cubic metre; m^3/d = cubic metre per day
mm	millimetre
mPa	millipascal
mK/m	millikelvin per metre
W/mK	Watts per metre degree Kelvin
psi	pounds per square inch (unit of pressure, British system)
yd^3	cubic yards

1. INTRODUCTION

The Norman Wells Pipeline, owned and operated by Interprovincial Pipe Line (NW) Ltd., is the first completely buried oil pipeline in the discontinuous permafrost zone of northern Canada. Along its 869 km (540 mi) route from Norman Wells, N.W.T., to Zama, Alberta, the pipeline traverses many permafrost slopes, considerable ice-rich thaw-sensitive terrain, many interfaces between frozen and unfrozen ground, and numerous water crossings, including major water crossings at Great Bear River and the Mackenzie River (Figure 1-1). Site specific geotechnical evaluations and designs were developed for 165 slopes and 57 water crossings. Examples of slopes with specific designs are illustrated in Figure 1-2 (Ochre River) and in the frontispiece photograph (Canyon Creek).

Under a special "Environmental Agreement", the pipeline project is subject to the "principle of minimum practicable environmental and land use disturbance". Permafrost and terrain monitoring was established to evaluate impacts and identify improvements for this and future projects.

Major new approaches to the design and environmental impact mitigation have involved minimizing the length of pipeline in thaw-sensitive terrain, minimizing the energy input from the pipeline to ice-rich terrain (small pipe, initially chilled oil), locating the pipe in previously cleared terrain, retarding or preventing thaw of sensitive slopes (wood chip insulation), increasing the strength of the pipe (pipe grade, wall thickness), and frequent monitoring and rapid response to unstable conditions (e.g. drainage and erosion control problems). These and other engineering and environmental considerations related to Norman Wells Pipeline design, environmental assessment, construction and operation are reviewed in Volume I of this report. Table 3-12 in Volume I summarizes some of the major overland pipeline and terrain related mitigative approaches employed on the pipeline project.

This Volume focuses on the Permafrost and Terrain Research and Monitoring Program, the results on selected topics relevant to design and impact mitigation, and recommendations for this and future northern development projects. Subsequent chapters emphasize:

(1) methods, procedures and data bases
(2) the climatic perspective during monitoring
(3) selected parameters needed to evaluate the thermal behaviour of the pipeline: pipe and ground temperatures, thaw depths, thaw settlement,
(4) overall terrain conditions during construction and operations, and
(5) the thermal performance of wood chip insulation.

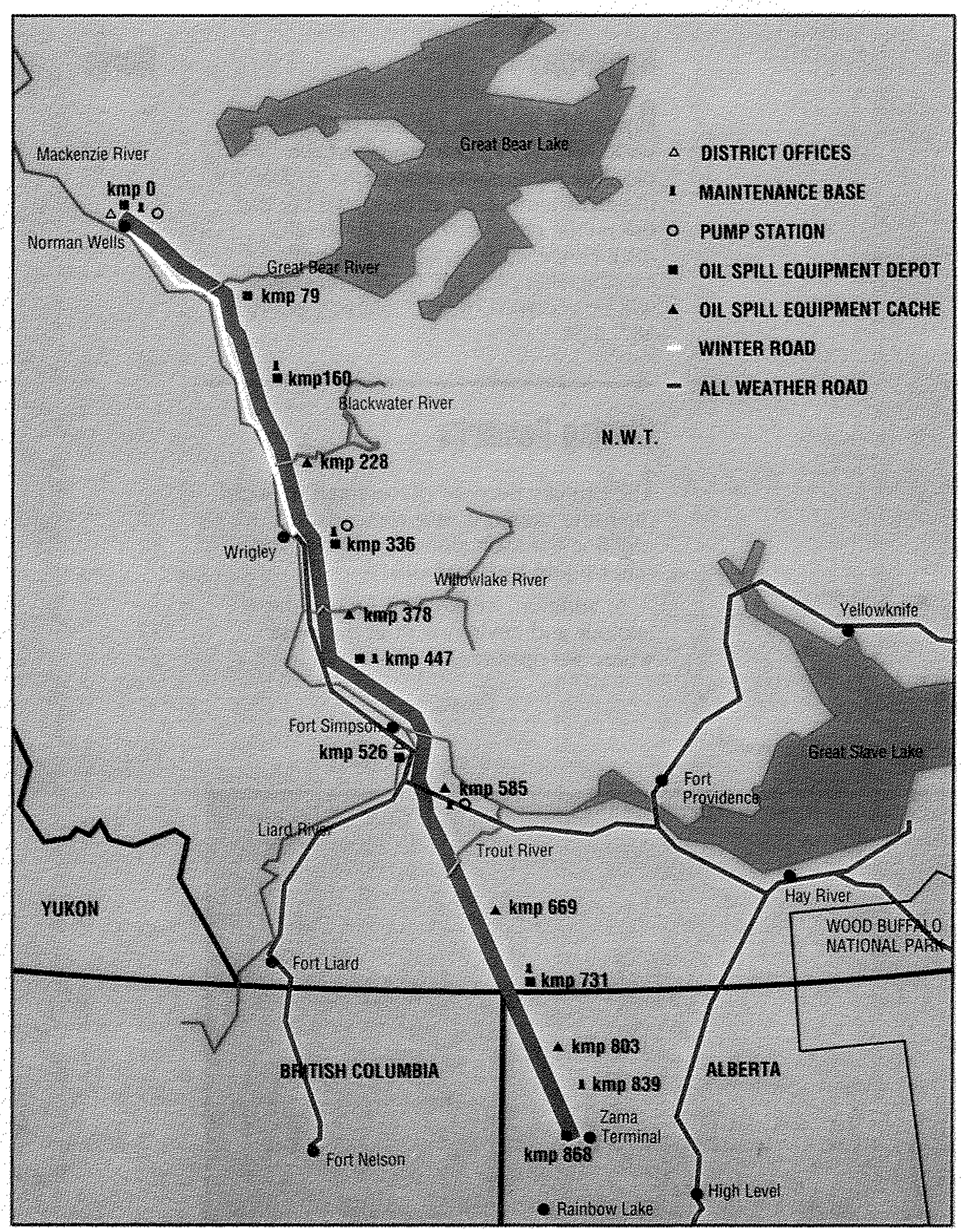

Figure 1-1. Norman Wells to Zama Pipeline alignment showing kilometre locations.

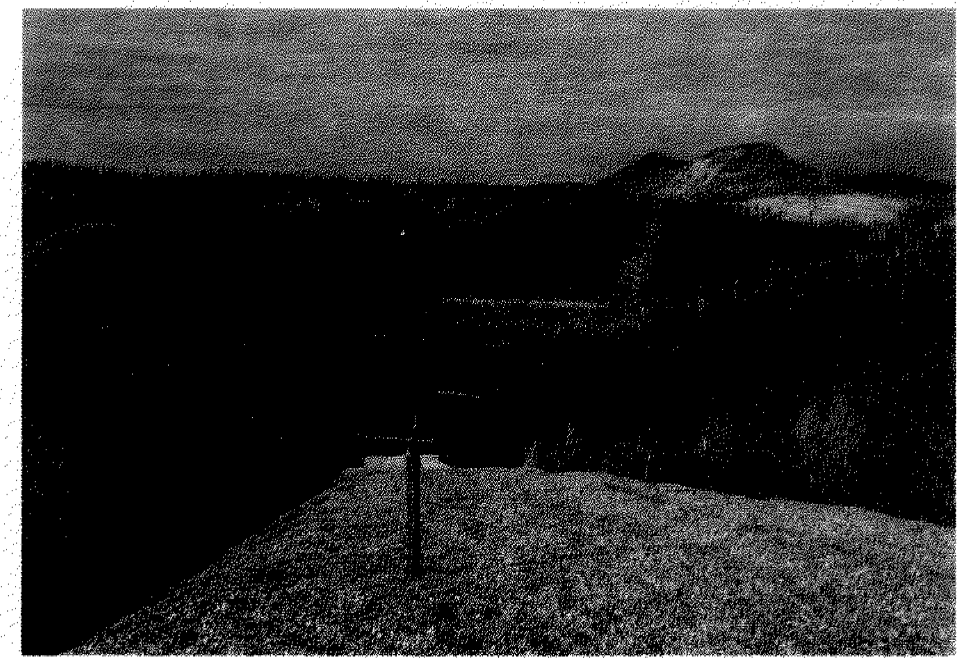

Figure 1-2. Examples of specific pipeline slope designs on the north (background) and south slopes of the Ochre River at km 286 (Sept. 1985). Wood chip slope in foreground contains IPL instrumentation to monitor wood chip and ground temperatures and soil moisture.

Observations and results are compared to the expected or predicted responses outlined by IPL during the pipeline project's conceptual and final design and assessment phases.

For reference, glossaries of some permafrost and pipeline related terms are given in Appendix A. The pipeline locations or "chainages" used for this report and for monitoring activities in general refer to the "As Built" chainages, unless indicated otherwise. Locations along the right-of-way are usually designated relative to the pipeline: north is toward Norman Wells and south is toward Zama. East and west refer to the respective sides of the right-of-way. Kilometre 0.0 is at the Norman Wells Pump Station (Figure 1-3).

Figure 1-3. Kilometre 0.0 of the Norman Wells Pipeline is at the Norman Wells Pump Station (lower right). Note adjacent ESSO fuel tank and flare stack.

2. PERMAFROST AND TERRAIN RESEARCH AND MONITORING

2.1 OBJECTIVES AND PARTICIPANTS

The Departments of Indian and Northern Affairs (INAC) and Energy, Mines, and Resources (EMR) initiated preliminary plans in 1983 for a co-operative permafrost and terrain research and monitoring program with Interprovincial Pipe Line (NW) Ltd. under the "Environmental Agreement" signed between IPL and the Minister of Indian and Northern Affairs (Appendix D in Volume I). The research and monitoring goal, as established in the Environmental Agreement, is to improve impact evaluation and mitigation on the Norman Wells pipeline and future projects.

The initial program consisted of two projects: (1) to monitor permafrost, terrain and terrain stability along the right-of-way by instrumenting selected sites (Permafrost Research Section, Earth Physics Branch, Geological Survey of Canada) and (2) to evaluate terrain performance along the right-of-way by periodic observation (Engineering Geology and Geomorphic Processes Section, Geological Survey of Canada). Two additional projects were initiated in 1986 to augment (a) the evaluation of wood chip insulation (Institute for Research in Construction, National Research Council) and (b) the evaluation of near surface (0.025 m to 1.5 m) soil temperatures and conditions (Land Resources Research Centre, Agriculture Canada). Results from the latter project will be presented in subsequent reports.

The Permafrost and Terrain Research and Monitoring (PTRM) Program objectives are (1) to determine and quantify impacts on permafrost and terrain, (2) to evaluate recovery processes and effectiveness of mitigative measures, (3) to compare actual and predicted impacts, (4) to assess the adequacy of the regional environmental framework and (5) to recommend improved environmental practices (Table 2-1). Specific objectives for each project are listed in Tables 2-2 and 2-3. The objectives were also established to address goals of the Norman Wells Research and Monitoring Working Group, the federal/territorial/native committee brought together by the Environmental Protection Service of Environment Canada at the request of the Government of the Northwest Territories (Boreal Ecology, 1989). Monitoring is planned for 5 to 10 years or until conditions stabilize (e.g. little evidence of erosion and settlement, or slope, streambank and thermal instability).

The "research and monitoring program" is distinct from (1) the pipeline operator's monitoring (e.g. standard operational line patrols; geotechnical and other environmental or pipe condition

Table 2-1. Overall program objectives for the Permafrost and Terrain Research and Monitoring Program 1983-1989.

(1) to determine and quantify the impacts of pipeline construction, operation maintenance, and abandonment on permafrost and northern terrain
(2) to evaluate the recovery processes and the effectiveness of short and long term mitigative measures
(3) to compare actual and predicted impacts in order to improve planning, design, impact management, and mitigation of northern pipelines
(4) to assess the adequacy of the regional environmental framework including terrain, climate and climate change, for the design and planning of northern pipelines
(5) to recommend improved environmental practices for future northern pipelines

monitoring) and (2) the legal regulatory surveillance and monitoring pursuant to Acts and Regulations. It works in close cooperation with both the Company and relevant regulators and shares the same broad goal of identifying impacts and improving mitigation. Any potential problems identified during monitoring field trips (e.g. exposed pipe, tension cracks, streambank erosion) are identified immediately to both IPL and INAC regulatory staff, in some cases directly via helicopter radio or telephone contact. Thermal data are provided to the Company immediately after each field trip and released to the public annually in GSC Open File reports. IPL wood chip thermal data, which are considered proprietary until January 1990, will be available after that date.

The PTRM observations also contribute to the performance evaluation required annually under the Environmental Agreement between INAC and IPL. The Environmental Agreement continues until the pipeline easement is terminated or surrendered, or until the pipeline is abandoned or removed.

Funding (1983-1988) for projects 1, 3 and 4 has come primarily from the Northern Affairs Program (NWT Region) of Indian and Northern Affairs supplemented with contributions from the Pipeline Coordination Office, the former Arctic Land Use Research Program, the former Northern Oil and Gas Action Program (NOGAP) and the Environmental Studies Division (INAC, Ottawa). Additional funding and contributions were provided from the program on Energy Research and Development (PERD), Energy, Mines, and Resources, National Research Council and Agriculture Canada. Lead funding for project 2 has come primarily from the program on Energy Research and Development (PERD) of Energy, Mines and Resources.

Table 2-2. Initial projects in the government Permafrost and Terrain Research and Monitoring Program.

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1. **Title**: Project to monitor permafrost, terrain and terrain stability on the Norman Wells, N.W.T. to Zama, Alberta Pipeline

   Lead Agency: Permafrost Research Section — J. Pilon
   Geological Survey of Canada — A.S. Judge
   Department of Energy, Mines, and Resources — M. Burgess
   (formerly Earth Physics Branch)

   Start-up Date: 1983 **Duration**: Phase 1 1983-1989

   Objectives:

   1. to monitor short and long term changes in the active layer, in permafrost and in terrain stability of the alignment area in relation to pipeline development and climatic change at selected study sites
   2. to assess the changes to the thermal and physical condition of terrain caused by pipeline related activity, including right-of-way clearance, pipeline installation, operation and maintenance
   3. to compare observed terrain conditions with those predicted during the pipeline design process, including thaw depth, thaw settlement, and frost heave of the surface
   4. to evaluate the effectiveness of mitigation and restoration procedures, and recovery at the study sites, including thermal performance of the pipe, wood chip insulation of slopes, drainage control, and revegetation
   5. to identify practical improvements which might be made in the planning, construction, operation, monitoring, and abandonment of future northern pipelines with special reference to the assessment of environmental impact including route selection, thermal design, ground surface protection, land stabilization, and restoration

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2. **Title**: Terrain performance research and monitoring, Norman Wells Pipeline.

   Lead Agency: Engineering Geology and Geomorphic Processes Section — D.G. Harry
   Geological Survey of Canada
   Department of Energy, Mines, and Resources

   Start-up Date: August, 1983 **Duration**: Phase 1 1983-1989

   Objectives:

   1. to determine the nature of geomorphic and geologic factor influencing terrain performance along the pipeline right-of-way.
   2. to evaluate actual terrain impacts with respect to predictions made at the project review stage, and in relation to mitigative measures incorporated within the pipeline design.
   3. to evaluate the concept of northern terrain sensitivity in relation to pipeline construction, operation, and maintenance activities.

Table 2-3. Projects added to the permafrost and terrain research and monitoring program in 1986.

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3. **Title**: Evaluation of Wood Chip Insulation on Selected Thaw-Sensitive Slopes Along the Norman Wells to Zama Pipeline

Lead Agency: Institute for Research in Construction National Research Council of Canada; (for Indian and Northern Affairs Canada) — T.H.W. Baker

Start-up Date: September 1986 **Duration**: 1986-1990

Objectives:

1. to evaluate the use of wood chips to prevent or retard thaw of ice-rich permafrost slopes
2. to measure the long term thermal properties of wood chip insulation
3. to develop a thermal model of wood chip performance for use in future designs
4. to compare wood chips with other alternatives to insulate ice-rich permafrost slopes

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4. **Title**: Norman Wells Pipeline Soil Temperature Study

Lead Agency: Land Resource Research Centre Agriculture Canada — C. Tarnocai

Start-up Date: April 1, 1986 **Duration**: Phase 1 1986-1990

Objectives:

1. to determine thermal changes in the soil (in both the active layer and the near-surface permafrost) caused by pipeline related activities, including right-of-way clearance and pipeline installation, operation, and maintenance

2. to assess the short and long-term environmental and soil climatic changes resulting from these thermal changes

3. to compare the actual thermal changes in the soil with the predicted changes in order to recommend improvements in planning and design so that the environmental impact of future northern pipelines will be minimized

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2.2 APPROACHES AND PROCEDURES

There were several special considerations for developing the research and monitoring program. Key considerations involved (1) goals of government-industry cooperation, established by a special agreement, (2) an operational oil pipeline, (3) government environmental protection concerns and responsibilities and (4) remoteness (accessibility) of most of the pipeline right-of-way, especially during the summer thaw period when terrain is most likely to be unstable. Because of the expensive access the first priority was to avoid duplication of effort and to maximize documentation.

The Earth Physics Branch and later the Geological Survey of Canada took the lead in the design, selection, and thermal instrumentation of EMR/INAC monitoring sites. This involved consultation and close cooperation with IPL and their consultants.

Both IPL and government identified contacts responsible for coordination and communication and established acceptable rules and procedures for communications, cooperation, safety, instrumentation, data exchange, and reporting. For example, IPL agreed to the placement of thermistors around the outside of the pipe, the instrumentation was standardized with the design used by IPL and IPL staff installed the pipe thermistors at government instrumented sites. Certain data were identified as proprietary and a mutually agreed release date was established. All other data are publicly available.

To meet INAC environmental protection concerns and responsibilities, INAC staff play a major role in developing and coordinating the research and monitoring, in field data collection and observation, and in interactions with pipeline staff, with researchers in other government departments, and with northerners. Photographic documentation which contributes to the performance evaluation required annually under the Environmental Agreement is on file in the Land Resources Division (INAC) in Yellowknife. Photographs are also on file with the Geological Survey of Canada, Ottawa.

Field observations for 1984 to 1987 were approximately monthly for most of the N.W.T portion of the right-of-way; the summer months, May through October, receiving the highest priority for thermal and associated observations at selected sites and for observation of overall right-of-way conditions (e.g. drainage changes, erosion channels, tension cracks, exposed pipe, slope movements, water crossing changes, ground settlement). District INAC staff (Land Use Inspectors and Water Officers) may supplement right-of-way observations after known major rainfall events. From November to April, data collection is primarily limited to sites near Norman Wells and Fort Simpson (1984-1986); this was increased to include the Wrigley area in 1987. Automatic loggers are used for more frequent thermal data acquisition. Results have been used, amongst other purposes, to evaluate thermal data collection frequency (Burgess and Riseborough, 1989), one of the criteria for scheduling monitoring trips. The frequency of field monitoring was reduced to 6-8 week intervals in 1988, retaining the emphasis on the thaw season. A schedule of all permafrost and terrain monitoring trips undertaken from 1983 to 1988 is given in Appendix Table B-1.

Monitoring generally requires helicopter access from either Norman Wells or Fort Simpson. Sites near Norman Wells and Fort Simpson are visited by truck or snowmobile in winter to reduce logistic costs.

Aspects of the research and monitoring reporting schedule have also been adjusted to field and northern project schedules. During the summer months, researchers are required to submit a field monitoring report to IPL and INAC immediately following field work (3-5 days). A technical review meeting is held each November with IPL; NEB and GNWT (1988) attend as observers. This timing coordinates with IPL's completion of its Annual Report to the National Energy Board and with the planning of winter remedial work. The Permafrost and Terrain Research and Monitoring Program also prepares an annual fall progress report to IPL and INAC. From 1983 to 1987, annual meetings were held with, and reports prepared for, the Norman Wells Research and Monitoring Working Group (Environmental Protection Service, 1984; Boreal Ecology, 1985, 1986, 1987, and 1989a). Since the Working Group was terminated in 1987, annual reports are addressed to IPL and INAC (Land Resources Division, INAC, Yellowknife).

2.3 INSTRUMENTED SITES

A major component of the Permafrost and Terrain Research and Monitoring Program is the quantification of changes in the ground thermal regime and geomorphic conditions at instrumented monitoring sites. Thirteen principal monitoring sites were selected in 1983 to allow evaluation of the thermal and environmental effects of the small, buried uninsulated pipeline in warm and discontinuous permafrost, and to investigate the terrain response to particular pipeline design features and mitigative measures. Government also proposed locating pipe position indicators on the pipe at monitoring sites at the time of construction; however, this proposal was not accepted by the pipeline company. The site selection process and instrumentation are described in detail in the following sections. Additional methods for field work and analyses are discussed in subsequent chapters.

2.3.1 Site selection

Sites were selected by EMR (Permafrost Research Section, GSC) and INAC (Land Resources) staff in conjunction with the pipeline company and its consultants, following a close examination of 1) the surficial geology and terrain types, 2) lithological and ice "log" data from geotechnical boreholes along the alignment,

3) available ground thermal data, both from geotechnical boreholes along the route and other drillholes in the Mackenzie Valley (Judge, 1973) and 4) geophysical surveys to map permafrost conditions and frozen/unfrozen transitions (IPL, 1982e).

The 13 locations, eleven in the Northwest Territories and two in northwestern Alberta, include areas of thaw-sensitive terrain, frozen/unfrozen interfaces, and two permafrost slopes (one of which is insulated with wood chips). They also represent soil, permafrost and ground ice conditions throughout the discontinuous permafrost zone. Two of the sites are joint sites, with IPL instrumented wood chip slopes and adjacent government instrumentation on level terrain. The IPL geotechnical program involves the instrumentation and monitoring of 26 slopes, 17 of which are covered with a wood chip insulating layer (Chapter 3, Vol. I). The PTRM sites therefore emphasized the study of other, generally level, terrain conditions. Six sites were established in 1984 and seven in 1985.

Brief descriptions of the 13 sites are given in Table 2-4, in order of kilometrepost from North to South, and locations are shown in Figure 2.1. The kilometreposts given for sites are the final "As-Built" chainage. The history and final width of clearing at the sites are summarized in Table 2-5. Most of the sites vary from 21 to 27 m wide. The large clearing (67 m width) at site 84-3A is due to the access and staging area cleared for construction of the Great Bear River water crossing. Three sites (7B, 10A, 11) have additional cleared areas east of the right-of-way only. The pipe centerline was centered in the previously cleared lines (see Figure 4-2, Vol.I). Figure 4-3 (Vol.I) illustrates the layout of construction activities across the right-of-way. Further site establishment information, including aerial and ground photographs, site plans, contours, borehole stratigraphy, ice records and early ground temperature data, is compiled for both 1984 and 1985 sites in Pilon et. al., 1989.

2.3.2 Temperature instrumentation

Boreholes for temperature instrumentation were established at the sites using track-mounted drill equipment during the winter pipe laying activities. Twelve of the monitoring sites have from one to three instrumented cross-sections, or "thermal fences". In total there are 23 fences. Where there is more than one fence at a site, fences are designated A, B, C in a north to south sequence. These sites or thermal fences may also be referred to as EMR/INAC sites to distinguish them from IPL sites.

The design of a thermal fence is as follows. At each fence, 5 temperature sensors, located on the outside of the pipe and installed by IPL prior to trench backfilling, provide a reference value for the pipe induced thermal disturbance. Two 5 m cables are located close to the pipe (within 3 m) to examine the immediate

Table 2-4. Permafrost and Terrain Research and Monitoring Site Descriptions.

No.	NAME		KM	DESCRIPTION (at time of establishment)
84-1	**Pump Station 1.......**			**Widespread permafrost**
			0.02	Ice-rich silty clay
84-2	**Canyon Creek.........**			**Previously cleared alignment, thaw-sensitive slopes, widespread permafrost.**
		A	19.0	Level location, frozen till with low ice content
		B	19.3	East-facing slope with a 1 m insulating wood chip cover
		C	19.6	Uninsulated section of west-facing slope
84-3	**Great Bear River.....**			**Joint IPL site with thaw-sensitive slope**
		A	79.2	Stratigraphically complex ice-rich alluvial terrace deposits, cliff-base
		B	79.4	Cliff-top lacustrine deposits with veneer of aeolian deposits
85-7	**Table Mountain.......**			**Joint IPL site with thaw-sensitive slopes**
		A	271.2	Ice-rich lacustrine plain(old seismic line)
		B	272.0	Drillpad clearing at bend on top of north facing slope, ice-rich lacustrine plain
		C	272.3	New clearing on ice-rich lacustrine plain
84-4	**Trail River..........**			**Pipeline previously traversed frozen ground**
		A	478.0	Unfrozen saturated sands/silts in dune hollow
		B	478.1	Dry sands and silts in dune crest
85-8	**Manner's Creek.......**			**Rapidly changing permafrost conditions**
		A	557.8	Thin peat with thick (10 m) permafrost
		B	558.2	Thick (2.7 m) peat with thin (4 m) permafrost
		C	558.3	Thin peat (1 m) with thin (1 m) permafrost
85-9	**Pump Station 3.......**			**Pipe previously traversed frozen section**
			583.3	Unfrozen granular soils
85-10	**Mackenzie Hwy.S......**			**Unfrozen/frozen interface**
		A	588.3	Transition from a helipad clearing in unfrozen terrain to
		B	588.7	Thin (3 m) permafrost with 2 m peat cover
85-11	**Moraine S.**		597.4	Thin (<4 m) permafrost in helipad clearing
85-12	**Jean Marie Creek.....**			**Unfrozen/frozen interface**
		A	608.6	Thin unfrozen peat
		B	608.7	Thick ice-rich peat plateau; 4 m permafrost
85-13	**Redknife Hills.......**			**Frozen/unfrozen interface; single cables only**
		A	682.2	Frozen (6 m) terrain surrounding large fen
		B	682.4	Frozen (6 m) terrain at fen border
		C	682.6	Unfrozen terrain in fen
84-5	**Petitot River N......**			**Degrading peat plateau**
		A	783.0	Ice-rich peat (3.5 m); 15-18 m permafrost
		B	783.3	Very thick icy peat (7 m); 12 m permafrost
84-6	**Petitot River S......**			**Peat plateau preceded by unfrozen fen**
			819.5	Thick (5 m) ice-rich peat; 7 m permafrost

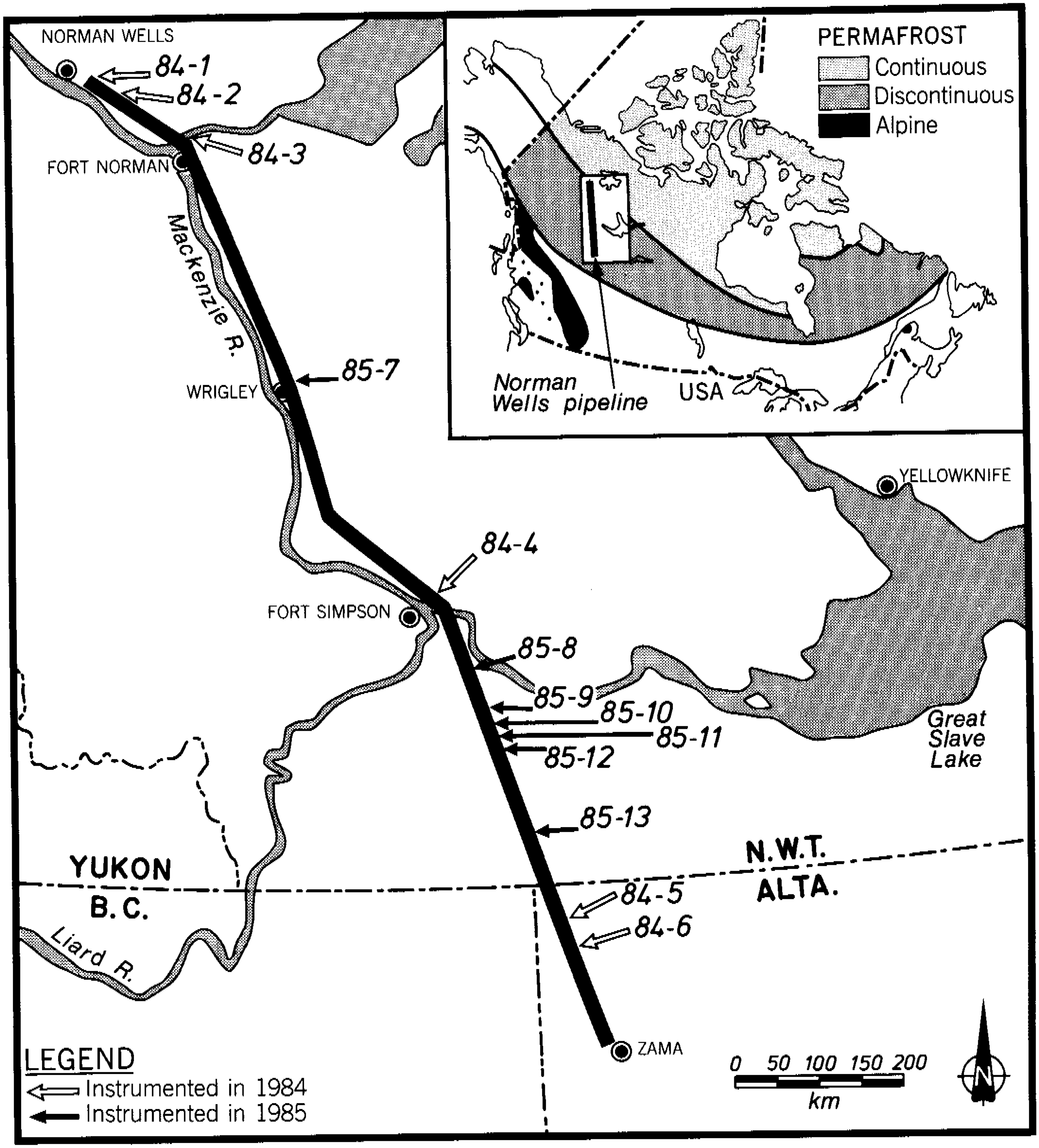


Figure 2-1. Location of permafrost and terrain research and monitoring sites.

Table 2-5. Right-of-way clearing history and dimensions at government thermal monitoring sites at the time of pipeline construction in winter 1984 or 1985.

SITE[1.] CODE	KMP	PREVIOUS CLEARING Y/N	Type	date	PIPELINE CLEARING date	width(m)	WORK SIDE (m)	SPOIL SIDE (m)
84-1	0.02	no	-	-	82/83	26.5	17.6	8.9
84-2A	19.0	yes	CNT[3]	1960's	82/83	25.1	14.3	10.8
2B	19.3	yes	CNT	1960's	82/83	21.4	11.2	10.2
2C	19.6	yes	CNt	1960's	82/83	21.7	11.0	10.7
84-3A	79.2	no	-	-	83/84	67.4	15+	10
3B	79.4	no	-	-	83/84	16.3	10.7	5.6
85-7A	271.2	yes	seismic	1960's	83/84	25.5	16.9	9.5
7B	272.0	yes	helipad	1982	83/84	25.2+	14.2	13.0
7C	272.3	no	-	-	83/84	24.3	14.3	10.0
84-4A	478.0	no	-	-	82/83	21.4	15.5	8.6
4B	478.1	no	-	-	82/83	24.5	14.8	9.7
85-8A	557.8	no	-	-	83/84	25.9	12.3	13.6
8B	558.2	no	-	-	83/84	24.8	13.0	11.8
8C	558.3	no	-	-	83/84	23.6	12.25	11.35
85-9	583.3	no	-	-	83/84	23.1	14.3	8.8
85-10A	588.3	yes	helipad	1982	83/84	26.7+	17.5	9.2
10B	588.7	no	-	-	83/84	26.3	17.5	8.6
85-11	597.4	yes	helipad	1982	83/84	25.7+	14.8	10.9
85-12A	608.6	no	-	-	83/84	25.7	15.8	9.9
12B	608.7	no	-	-	83/84	24.8	15.0	9.8
84-5A	783.0	no	-	-	82/83	25.2	15.3	9.9
5B	783.3	no	-	-	82/83	26.0	14.2	11.8
84-6	819.5	no	-	-	82/83	25.0	15.0	9.0

1. Sites 7B, 10A and 11 are partly within or adjacent to 1982 helipad clearings for geotechnical boreholes. Sites 2A, 2B, 2C and 7A were previously cleared in the 1960's.
2. Previous clearing primarily refers to tree removal although it may also include other disturbance to the surface (e.g. removal of ground vegetation or organic material).

effect of pipeline trenching, installation and operation on ground temperature. Two 20 m (or near 20 m) cables, one on the right-of-way (ROW) generally designated as T3 and located 4 to 10 m from the pipe, and the other off the ROW (generally designated as T4), are used to investigate the deeper thermal characteristics and to enable a comparison of the thermal regime of the ROW and the surrounding terrain.

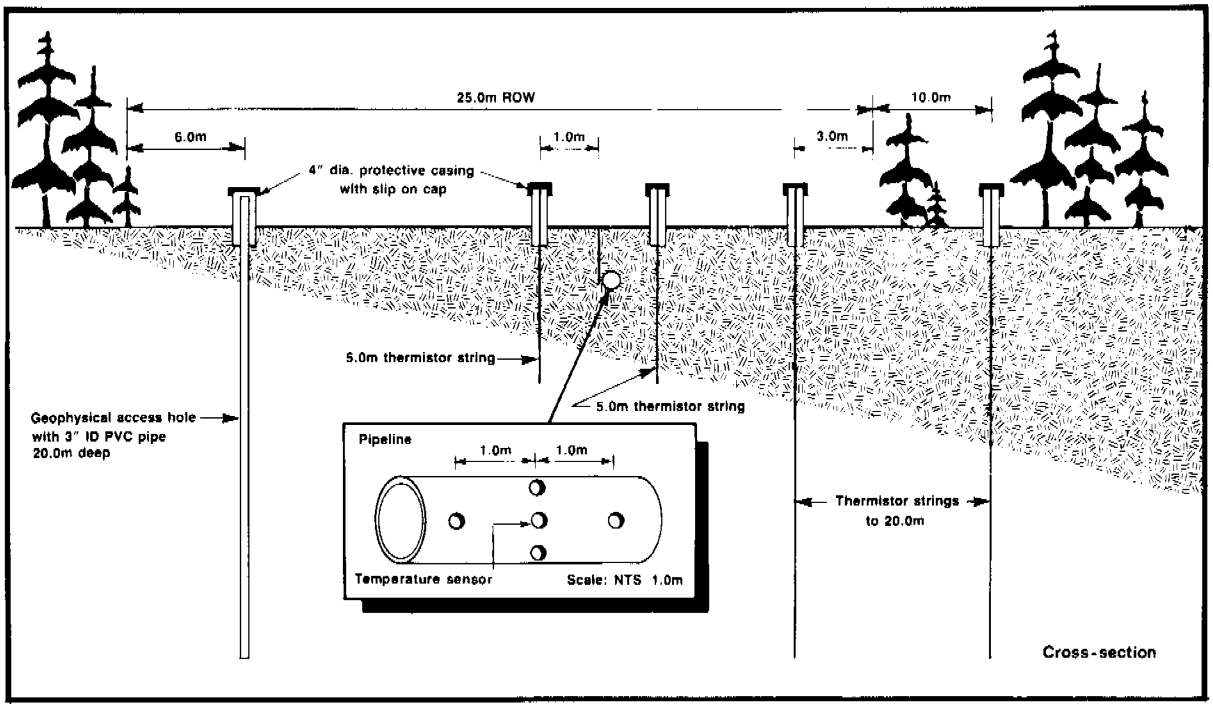
An example of the layout of a fence is illustrated in Figure 2-2. The two short cables in this layout are located on each side of the ditch. This design was modified for the three northernmost sites where the spoil side was not accessible during drilling which preceded ditch backfilling; here the two short cables are located on the same side (i.e. the travel side) of the ditch. Although care was taken in drilling off the ROW, some disturbance to tree cover, ground cover and surface conditions occurred at some sites during the borehole drilling with track-mounted drills. Disturbance Grading of the ground surface was a major concern at the Table Mountain sites (km 271). New off-ROW holes were drilled in 1986 (cables HA-108 to HA-110). Unlike the other sites, the Redknife Hills site has three cables on the ROW, spaced 200 m in a line paralleling the pipe, in order to examine the transition from frozen mineral terrain to unfrozen fen. Figures 2-3 and 2-4 show sites 84-1 and 84-3A in 1984 and in 1988.

There are currently (1988) 109 temperature cables installed at the main EMR/INAC monitoring sites. The number and lengths of cables installed in the boreholes at the main monitoring sites are summarized in Table 2-6. Further details on boreholes, their distance from the pipe at each fence, the number of temperature sensors in each cable and the sensor spacings are contained in the site establishment report (Pilon et al., 1989) and in annual listings of temperature data published as GSC Open Files.

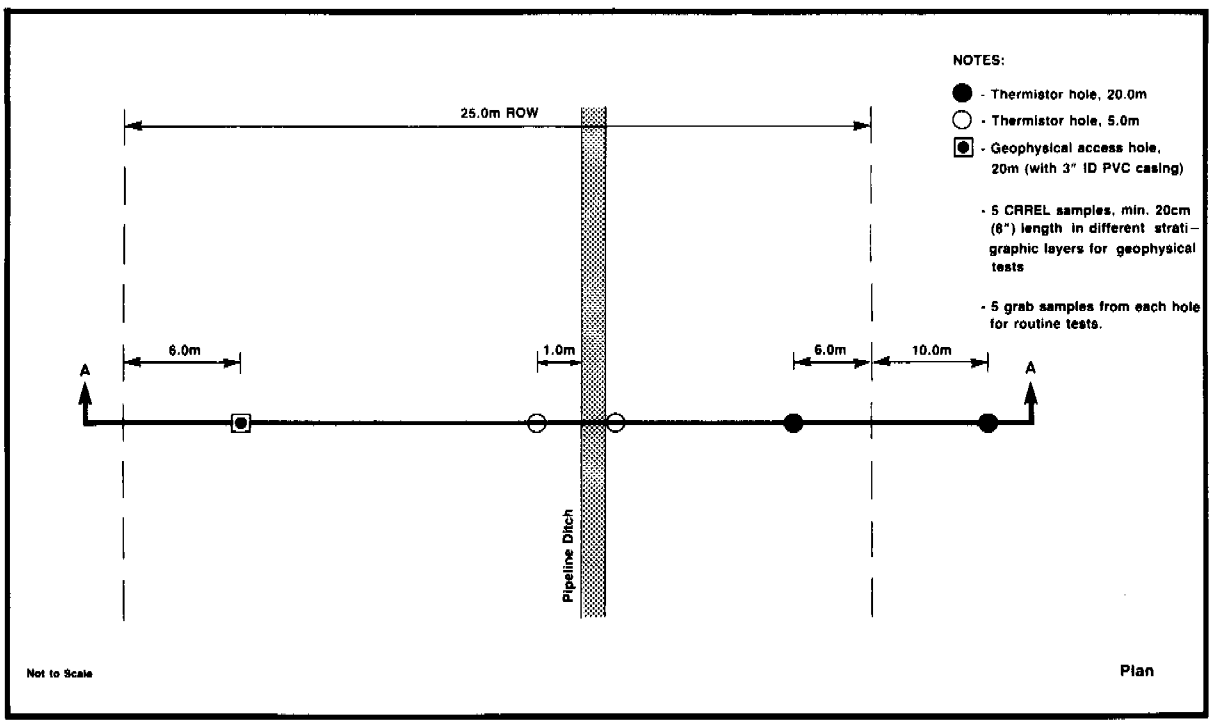
Borehole stratigraphic records (logs), visual ice logs and preliminary geotechnical data were collected as part of the drilling program and are compiled in two contract reports (Hardy Associates, 1984 and 1985). An additional large diameter access hole was drilled on the ROW at each fence to a target depth of 20 m and cased with 76 mm polyvinyl chloride (PVC) tubing for long term downhole geophysical logging. Continuous core samples were retained from the drilling of geophysical holes at the 1985 sites and laboratory investigations of the physical, thermal and electrical properties of these frozen cores are underway (Patterson et al., 1988; Patterson and Riseborough, 1988).

Detailed information on the type of instrumentation, the accuracy of the temperature sensors, the installation procedure and the field measurement procedure used at the sites is discussed by Burgess (1987). Briefly, the shorter cables contain ten thermistor sensors (semi-conductor devices whose electrical resistance varies inversely with temperature) spaced every 50 cm; the longer cables contain eleven thermistors, spaced every metre near the surface and then every 2 or 3 m at depth. Three types of sensors have been used:

1) YSI44033, the most common
2) YSI44032, installed at two fences in Alberta, and
3) ATKINS, 1984 pipe thermistors.



a) cross-section



b) aerial view

Figure 2-2. An example of the layout of a typical thermal fence.

Figure 2-3. Site 84-1 at Norman Wells September 19, 1984 (above) and May 24, 1988 (below, view south from the Pump Station 1 gravel pad).

Figure 2-4. Site 84-3A south of the Great Bear River at Fort Norman September 20, 1984 (above) and September 13, 1988 (below, view south).

Table 2-6. Number and lengths of cables installed in boreholes at the main Permafrost and Terrain Research and Monitoring sites.

NO.	NAME	CABLES	KM	CABLE LENGTH (METRES) T1	T2	T3	T4	OTHER CABLES (METRES)
84-1		5	0.02	5.1	5.0	10.4	13.6	(T5,19.6)
84-2	A	4 (+3)	19.0	5.3	5.1	19.6	13.0	(HT140, 45.0) (HT138,100.0) (HT153,128.0)
	B	4	19.3	5.8	5.9	20.5	20.6	
	C	4	19.6	5.8	5.5	19.4	20.0	
84-3	A	4	79.2	4.7	4.7	22.1	8.0	
	B	4	79.4	6.3	6.3	21.4	20.9	
85-7	A	6	271.2	5.0	5.0	20.0	20.0	(HA108,20.0) (HA111,93.0)
	B	7	272.0	5.0	5.0	20.0	20.0	(HA110,20.0) (HA129,10.0) (HA130,10.0)
	C	5	272.3	5.0	5.0	20.0	20.0	(HA109, 20.0)
84-4	A	4	478.0	20.0	20.0	5.0	5.0	
	B	4	478.1	9.0	5.5	5.5	20.0	
85-8	A	4	557.8	5.0	5.0	20.0	20.0	
	B	4	558.2	5.0	5.0	20.0	20.0	
	C	4	558.3	5.0	5.0	20.0	20.0	
85-9		4	585.3	5.0	5.0	20.0	20.0	
85-10	A	4	588.3	5.0	5.0	20.0	20.0	
	B	4	588.7	5.0	5.0	10.5	10.5	
85-11		4	597.4	5.0	5.0	12.0	12.0	
85-12	A	5	608.6	5.0	5.0	7.0	12.0	(T3A, 16.4)
	B	6	608.7	5.0	5.0	17.2	9.7	(HA133, 5.7) (HA134, 7.4)
85-13	A	1	682.2	----	----	----	----	(13A, 20.0)
	B	1	682.4	----	----	----	----	(13B, 10.5)
	C	1	682.6	----	----	----	----	(13C, 4.5)
84-5	A	4	783.0	5.2	5.6	20.6	20.6	
	B	4	783.3	5.5	5.7	20.5	20.5	
84-6		5	819.5	5.5	5.4	20.6	20.7	(T-5, 10.1)

Note: Trail River cables are not typical (At 4A, T2 is off ROW and T1 is the deep cable on the ROW. At 4B, T4 is off ROW and T1 is the deep cable on the ROW).
HT Cables at Canyon Creek 2A are part of deep climate installation
Total cables at main sites = 106 (109)

The YSI thermistors are calibrated to an accuracy of 0.1 K. The resolution of the measuring system is greater, and relative changes of 0.01 K may be resolved.

The ground temperature cables are installed in small diameter (25-38 mm) PVC tubes filled with an environmentally safe non-freezing silicone oil to allow for cable removal or replacement. Silicone fluid viscosity was selected to minimize convective overturn in the boreholes. Temperature cables were installed throughout the summer of 1984 for the winter 1984 sites, and in March 1985 for the 1985 sites (Figure 2-5). The depth positioning of the cables was relative to the ground surface at the time of cable installation. Thus, although the sensor spacing along the cable remains constant with time, the absolute depth of the sensors with respect to the surface level may change as the surface is subjected to heave or settlement. The base of the small PVC tube is firmly anchored in the ground and thus the top of the tube provides a stable datum.

Cable positions relative to the changing ground surface are determined using the settlement/heave data from topographical surveys and by periodically remeasuring the depth of the first sensor on each cable. An evaluation of the initial cable positions, relative to the ground surface, and remeasured cable positions in October 1988, are discussed in Burgess and Naufal, 1990.

A few replacement cables have been required, generally to replace 44032 sensors with 44033 for compatibility with automatic SeaData loggers, or, in two instances, when 2-3 sensors have failed within a thermistor cable. As of December 1989, one thermistor sensor has failed on each of 15 cables. Of the over 1200 thermistor sensors in use, this represents a failure rate of approximately 1-2%.

2.3.3 Frequency of temperature data collection

From 1984 to 1987, manual temperature data were collected approximately monthly at the most important or easily accessible sites. Remote sites in N.W.T. (85-7, 85-13) and sites outside the N.W.T. (84-5, 84-6) are not regularly visited in the winter. Regular winter data collection at site 85-7 near Wrigley was established in 1987. In 1988, the temperature data collection was generally reduced to 6-8 week intervals, retaining the emphasis on the thaw season. Winter readings have been primarily undertaken by INAC district staff from Norman Wells and Fort Simpson. EMR or INAC researchers have been responsible for monthly data collection during the summer thaw season from May to October.

Figure 2-5. March 1985 installation of temperature cable T3A at Jean Marie site 85-12A.

Since October 1985, seven thermal fences have been equipped with 64 channel automatic data loggers (SeaData model 1250B) to allow for more continuous data gathering at remote locations or sites of special interest (Table 2-7). These loggers are connected to the EMR/INAC ground temperature cables.

Table 2-7. Location of 64 channel SeaData automatic loggers at thermal fences along the pipeline.

LOCATION	KM	DATE	COMMENTS
84-2A	19.0	October 1985	Coordinate with climate station
84-3A	79.2	October 1985	Ice-rich site undergoing thaw settlement
84-7A	271.2	October 1985	Extend data coverage (winter)
84-7B	272.0	October 1985	Extend data coverage (winter)
84-7C	272.3	October 1987	Extend data coverage (winter)
85-12B	608.7	October 1988	Extend data coverage - Peat plateau
84-5B	783.3	October 1986	Extend data coverage - Peat plateau (Alberta)

More frequent measurements were of interest at Canyon Creek fence 84-2A to complement the automated micrometeorological data collected by the Atmospheric Environment Service of Environment Canada at their climate station installed in the winter of 1985 (Granberg, 1985; Etkin et al., 1988). At Great Bear fence 84-3A, where pronounced thaw settlement with the development of hummocky terrain had occurred on the ROW, a more detailed monitoring of the ground thermal regime in the ice-rich surficial material was desired. A logger was installed at fence 84-5B Petitot River North in northern Alberta to ensure continuous data coverage at a minimum of one site in the peat plateaux of northern Alberta. A logger was installed on a second peat plateau at fence 85-12B in the N.W.T..

The SeaData automatic data acquisition systems may be left unattended for up to 6 months. The data loggers are currently set for 3 readings per day. Logger tape and battery changes are scheduled twice a year, in the spring and fall (generally May and October).

Pipe temperature sensors were not connected to the SeaData loggers because of sensor and/or connector incompatibility. To obtain more frequent pipe temperature readings, an additional sensor was installed beside the pipe at 11 fences (1, 2A, 3A, 7B, 7C, 4B, 8A, 10A, 12B, 13C, 5B) and connected to a separate single channel logger (model RBL TL-100) in August 1986 (AG-CAN/INAC project). These loggers are set to read hourly or every 3 hours. These data are available from C. Tarnocai, AG-CAN. Results from the logger pipe temperatures have been presented in the 1987 to 1989 Annual Progress Reports to IPL and INAC.

Tables of ground temperature and pipe temperature data collected at the EMR/INAC monitoring sites are published annually as Geological Survey of Canada Open Files (Burgess, 1986 and 1987; Burgess and Naufal, 1989 and 1990). Table B-2 in Appendix B summarizes the measurement statistics for each cable through December 1987 (date installed, actual readings/yr). The data base are maintained with the GSC's Terrain Sciences Division. Data are available through M. Burgess or A. Judge.

2.3.4 Associated instrumentation and data collection

Topography Surveys

In order to determine amounts and rates of surface thaw settlement and whether sites are stable, level surveys are conducted to record vertical movements in the ground surface to an accuracy of +/- 10 cm over a 20 m by 20 m or larger grid using 2-3 local benchmarks per site and generally a 2 m station spacing. Initial benchmarks were local trees; subsequent benchmarks include the small diameter PVC tubes in deep holes where tubes are frozen into permafrost. Station spacing has occasionally been reduced to 1 m to map the microrelief in better detail either in the vicinity of the trench at sites where the ditchline has subsided, or over the whole ROW at sites which have re-developed a hummocky terrain.

Surveys were initially conducted once a year in late summer. A few sites were surveyed semi-annually in the first year after their establishment. The frequency was subsequently decreased to every 2 or 3 years at more stable sites. The survey frequency was further reduced in 1988 to a minimum of every two years at sites, providing funding is available. No surveys were undertaken in 1988. Table 2-8 lists the sites and the dates of these topographic surveys. Survey contracts (1984-1988) were supervised by the Regional Surveyor's Office, EMR, Yellowknife and surveys are on file at their office in Yellowknife.

TABLE 2-8. Dates and locations of site topography surveys.

FENCE	KP	1984	SPRING 1985	FALL 1985	1986	1987
84-1	0.02	20/6/84	27/5/85	26/9/85	7/9/86	29/8/87
84-2A	19.0	21/8/84	-	-	17/9/86	-
84-2B	19.3	22/8/84	-	-	17/9/86	28/8/87
84-2C	19.6	22/8/84	-	-	17/9/86	-
84-3A	79.2	22/8/84	27/5/85	26/9/85	18/9/86	22/8/87
84-3B	79.4	22/8/84	27/5/85	26/9/85	18/9/86	22/8/87
85-7A	271.2	-	26/5/85	26/9/85	16/9/86	27/8/87
85-7B	272.0	-	26/5/85	26/9/85	16/9/86	27/8/87
85-7C	272.3	-	26/5/85	26/9/85	16/9/86	27/8/87
84-4A	478.0	24/8/84	-	-	15/9/86	-
84-4B	478.1	24/8/84	-	-	15/9/86	-
85-8A	557.8	-	25/5/85	26/9/85	12/9/86	26/8/87
85-8B	558.2	-	25/5/85	26/9/85	12/9/86	26/8/87
85-8C	558.3	-	25/5/85	26/9/85	12/9/86	26/8/87
85-9	583.3	-	24/5/85	-	13/9/86	-
85-10A	588.3	-	23/5/85	-	13/9/86	25/8/87
85-10B	588.7	-	23/5/85	-	13/9/86	25/8/87
85-11	597.4	-	23/5/85	-	14/9/86	-
85-12A	608.6	-	22/5/85	26/9/85	14/9/86	25/8/87
85-12B	608.7	-	22/5/85	26/9/85	14/9/86	25/8/87
84-5A	783.0	26/8/84	-	-	-	19/8/87
84-5B	783.3	25/8/84	-	-	-	19/8/87
84-6	819.5	25/8/84	-	-	-	19/8/87

Active layer probing

Two types of "active layer probes" have been used to obtain additional data on the active layer. One type, a stainless steel rod with a thermistor embedded in its tip, is used to obtain temperature data on the depth of the frost table. The second type, a steel probe, has been used to measure the depth to the frost. This probing has been repeated on transects across the right-of-way at selected sites close to the time of maximum active layer development in the fall. The profiles provide a comparison of conditions on and off the ROW and of differential active layer development on the ROW. These data are available from Terrain Sciences Division, GSC (D. Harry).

AG-CAN soil probes

In August 1986, 1.5 m soil temperature probes with seven thermistor sensors (2.5, 5, 10, 20, 50, 100, 150 cm) were installed at selected thermal fences (listed in Appendix B-3) to monitor the near-surface thermal regime both on and off ROW. The probes are rigid, consisting of a 2.5 cm diameter PVC pipe with thermistors (YSI 44033) imbedded into 1/8 in. diameter recessed holes. To ensure that sensors remain at a fairly constant depth beneath the ground surface, the soil probes are regularly measured and re-adjusted relative to the ground surface during the summer field trips. The zero mark, a groove on the outside of the PVC is re-aligned with the ground surface (defined as the base of living ground cover of lichens or mosses if present). In hummocky terrain, probes are installed on the top of the hummock. Soil probe data are available from C. Tarnocai, AG-CAN.

Ground probing radar (GPR) and Time domain reflectometry (TDR)

Ground probing radar (GPR) and time domain reflectometry (TDR) surveys have been taken to complement the thermal observations. The GPR provides a continuous transect of the active layer and shallow permafrost characteristics to depths of 10 m on average. The radar surveys are discussed in A Cubed Inc. (1985) and Pilon et al. (1985a and 1985b). Radar data and reports are available from J. Pilon, GSC. Repeat profiles at the thermal fences and on the wood chip slope at Great Bear River are available from A. Judge, GSC.

TDR installations provide (spring and fall) data on soil electrical properties and moisture conditions to depths of 2 m at three locations across the thermal fence: next to the pipeline, in the centre of the ROW and off-ROW. TDR data and reports are available from M. Burgess. The frequencies of TDR and GPR measurements through 1987 are given in Tables B-4 and B-5 in Appendix B.

Wood chip evaluation

As part of the NRC/INAC project to evaluate wood chip insulation of thaw-sensitive slopes additional instrumentation was placed at fence 84-2B in September 1986. Thermal conductivity probes, heat flow metres and temperatures sensors were installed in the wood chip layer to provide information on the long term changes in thermal properties of the wood chips. These data will be released in 1990 and will be available from T.H.W. Baker, National Research Council.

Snow depth

Hand measurements of snow depths on and off ROW at cable locations are made over the winter months. In addition two wooden permanent snow depth markers have been located at all fences, except 4B, 5A, 5B and 6. The markers are positioned near the soil probes, if present; otherwise they are located near the deeper cables (T3 and T4). Measurements of snow densities have been made using an MSC snow coring device (Figure 2-6, March monitoring trips 1986 - 1989). Snow density data are available from the INAC Water Resources Division, Yellowknife or from K. MacInnes, Land Resources Division.

Ditch thermistor strings

In the summer of 1986, IPL installed two thermistor cables in the ditch at six of the monitoring fences (2C, 3B, 7C, 4A, 8A and 9). These short cables, one directly above the pipe and the other at the ditch wall, are to provide data to help define the thermal regime of the pipe and ditch under specific conditions including subsided ditch with flowing water.

Temperature instrumentation at IPL thaw settlement sites

In the fall of 1986, drillholes at five IPL thaw settlement monitoring sites (IPL, 1986) were instrumented with EMR/INAC temperature cables to depths of 7 to 10 m. Two of these sites overlap with existing thermal fences (85-7B, 85-12B). The three other sites are located at kmp 95.2, 135.1 and 470.0. Two boreholes were instrumented at each site, except kmp 95.2 which has only one cable.

Figure 2-6. Measuring snow density at site 85-11 (12/3/87).

Deep boreholes and climate stations

Deep boreholes and climate stations have been established co-operatively by GSC, AES and INAC to provide long term reference sites for climate change and ground temperature monitoring in the Mackenzie Valley (Table 2-9). The first deep borehole was drilled at the Table Mountain 85-7A site near Wrigley in March 1986.

Table 2-9. Location of deep boreholes and special climate stations in the Mackenzie Valley.

LOCATION	DEEP BOREHOLE(S) Date	Depth(m)	CLIMATE STATION Date	Elevation (m)
Table Mountain 85-7A (63° 37'N, 123° 38'W)	Mar. 1986	93	---	255
Canyon Creek 84-2B (65° 14'N, 126° 31,W)	Mar. 1987	45 129	Mar. 1985	120
Kee Scarp (Norman Wells) (65° 17'N, 126° 53'W)	Mar. 1987	45 129	Aug. 1988	300
Gibson Gap (65° 46'N, 127° 55'W)	Mar. 1989	100	Aug. 1988	230

1. These climate and ground temperature monitoring sites have been established through cooperative work of AES, EMR and INAC.

Subsequent boreholes were drilled and instrumented at Canyon Creek, Kee Scarp and Gibson Gap. The climate stations at these latter sites are maintained and operated by A. Hedley (AES) and A. Judge (GSC). Data from the ground temperature cables are included in GSC Open Files (e.g. Burgess, 1987; Burgess and Naufal, 1989). Climate data are available from Atmospheric Environment Service, Downsview, Ontario (D. Etkin). Snow depths are recorded automatically at each climate station.

Magnetic Sensors

In May 1987 soil displacement gauges were installed at two monitoring fences for experimental examination of the dynamics of near-surface materials. The gauges consist of a series of ring magnets buried sequentially around teflon-covered access tubes to depths of 1.5 m. The measurement of the location of the magnets relative to the ground surface, accomplished by lowering a reed switch attached to a graduated cable, should enable monitoring of their relative displacements and thus indicate the amount of differential frost heave or thaw settlement. At site 84-1 (km 0.02) three gauges were installed (one off-ROW and two on-ROW); two gauges were also installed at 84-3A (km 79.2), one on and one off-ROW. Readings (May and October) are available from M. Burgess, GSC.

3. CLIMATIC CONDITIONS (1983-1989)

Many of the terrain responses to disturbance have been modified by climatic and related hydrological conditions experienced during and since pipeline construction. It is thus appropriate to review climatic conditions and departures from long-term (1951-1980) "normals" which have occurred during the period 1983-1989. Data have been analyzed from Environment Canada meteorological stations and seasonal stations located by the GNWT Forest Fire Centre (see Chapter 2, Vol.I, Tables 2-1 and 02-3). The latter data set has been used to provide additional information on local climatic conditions and climatic variability. Unofficial summaries of weather conditions within the pipeline corridor are prepared on a monthly basis and prior to monitoring trips during the thaw season.

Climatic data for the period 1983-1989 have been grouped by season, so that they may be related to the annual pattern of terrain impact and response. Thus, the "winter season" (October-April) includes the periods of clearing and construction on the pipeline right-of-way during the construction phase, and winter remedial programs during the post-construction phase. The most critical winter climatic parameters are air temperature and snowcover, both of which influence the degree of terrain disturbance caused by vehicle movement, grading and excavation as well as ground thermal conditions. Snow conditions have also influenced the thermal performance of wood chip insulation on slopes (Chapter 6). The timing of snowcover development is also an important factor in relation to pipeline construction and maintenance schedules.

The "summer season" (May-September) approximately corresponds to thaw conditions during which maximum terrain response to disturbance is likely to occur. During this season air temperature is again important, since it determines the duration and depth of ground thawing. In addition, both the total amount of precipitation and the frequency, magnitude and intensity of rainstorm events are important. They determine surface runoff and groundwater conditions and are a factor in the distribution of surface erosion and slope instability and in the active layer development.

Climate data recorded during the period 1983-1989 at Norman Wells, Fort Simpson and High Level are presented in Tables 3-1(a-c) (winter air temperature, total precipitation, snowfall) and Tables 3-2(a-b) (summer air temperature and total precipitation). Significant differences from the long-term (1951-1980) mean conditions are indicated on the tables in relation to the standard deviation of the climatic parameter. (Within a normally distributed data set, 68% of the data lie within one standard

Table 3-1 (a): Winter climatic conditions 1983-1989: air temperature

	Mean Daily Air Temperature (°C)								Difference From Normal (°C)						
Month/Station	Normal	1983	1984	1985	1986	1987	1988	1989	1983	1984	1985	1986	1987	1988	1989
OCTOBER															
Norman Wells A	-4.6	-7.4	-7.1	-6.9	-4.1	-0.7	-6.5	---	-2.8*	-2.5*	-2.3	-0.5	3.9*	-1.9	---
Fort Simpson A	-1.9	-4.8	-4.4	-3.9	-0.8	1.1	-2.4	---	-2.9*	-2.5*	-2.0	-1.1	3.0*	-0.5	---
High Level A	1.3	1.2	2.0	-1.5	-6.7	2.0	3.9	---	-0.1	-3.3**	-2.8*	5.4**	0.7	2.6*	---
NOVEMBER															
Norman Wells A	-18.2	-14.4	-24.6	-21.8	-23.6	-19.0	-24.5	---	3.8*	-6.4*	-3.6*	-5.4*	-0.8	-6.3*	---
Fort Simpson A	-15.6	-10.4	-18.3	-20.2	-19.6	-13.2	-18.6	---	5.2*	-2.7	-4.6*	-4.0*	2.4	-3.0	---
High Level A	-11.4	-7.0	-16.4	-19.9	-18.5	-8.1	-13.6	---	4.4*	-5.0*	-8.5**	-7.1*	3.3	-2.2	---
DECEMBER															
Norman Wells A	-26.5	-24.7	-28.0	-19.0	-19.5	-21.0	-20.4	---	1.8	-1.5	7.5**	7.0**	5.5*	6.1*	---
Fort Simpson A	-24.5	-25.8	-27.8	-17.8	-17.5	-19.5	-20.6	---	-1.3	-3.3	6.7*	7.0**	5.0*	3.9*	---
High Level A	-20.3	-25.6	-26.6	-14.9	-12.9	-13.8	-16.2	---	-5.3*	-6.3*	5.4*	7.4*	6.5*	4.1*	---
JANUARY															
Norman Wells A	-28.9	---	-26.3	-18.7	-27.9	-21.3	-26.1	-30.9	---	2.6	10.2**	1.0	7.6*	2.8	-2.0
Fort Simpson A	-28.2	---	-25.6	-17.3	-24.3	-17.5	-24.8	-29.3	---	2.6	10.9**	3.9*	10.7**	3.4	-1.1
High Level A	-24.6	---	-19.2	-15.4	-16.8	-14.6	-20.4	-22.8	---	5.4*	9.2**	7.8**	10.0**	4.2*	1.8
FEBRUARY															
Norman Wells A	-26.2	---	-26.9	-30.8	-20.9	-23.7	-23.5	-15.0	---	-0.7	-4.6*	5.3*	2.5	2.7	11.2**
Fort Simpson A	-22.8	---	-20.5	-28.8	-18.7	-17.8	-22.1	-15.0	---	2.3	-6.0*	4.1	5.0*	0.7	7.8*
High Level A	-18.5	---	-12.5	-24.1	-17.5	-12.4	-18.2	-16.7	---	6.0*	-5.6	1.0	6.1*	0.3	1.8
MARCH															
Norman Wells A	-19.8	---	-19.5	-16.2	-20.1	-19.7	-13.7	-21.9	---	0.4	3.6*	-0.3	0.1	6.1*	-2.1
Fort Simpson A	-14.9	---	-13.9	-9.3	-15.2	-14.3	-8.9	-18.2	---	1.0	5.6*	-0.3	0.6	6.0*	-3.3
High Level A	-11.8	---	-7.3	-6.8	-9.0	-13.6	-6.4	-16.6	---	4.5*	5.0**	2.8*	-1.8	5.4**	-4.8*
APRIL															
Norman Wells A	-7.2	---	-2.6	-11.5	-11.5	-7.1	-4.0	-3.1	---	4.6*	-4.3*	-4.3*	0.1	3.2*	4.1*
Fort Simpson A	-2.5	---	2.7	-3.0	-5.4	0.6	0.6	1.1	---	5.2*	-0.5	-2.9	3.1	3.1	3.6*
High Level A	0.8	---	5.3	1.3	-0.3	4.0	2.7	0.6	---	4.5*	0.5	-1.1	3.2	1.9	-0.2

Source: Atmospheric Environment Service, Environment Canada, Monthly Record.
Note: * = Difference > 1 Standard Deviation from Mean (68% significant)
** = Difference > 2 Standard Deviation from Mean (95% significant)

Table 3-1 (b): Winter climatic conditions 1983-1989: total precipitation

	Monthly Total Precipitation (cm)								Difference From Normal (%)						
Month/Station	Normal	1983	1984	1985	1986	1987	1988	1989	1983	1984	1985	1986	1987	1988	1989
OCTOBER															
Norman Wells A	26.8	28.7	40.6	22.5	21.1	46.5	31.2	---	107	151*	84	79	174*	116	---
Fort Simpson A	24.0	27.2	45.6	54.7	17.4	40.9	33.6	---	113	190**	228**	73	170*	140	---
High Level A	14.7	21.4	48.4	43.0	34.4	62.4	56.3	---	146	329**	293**	234*	424**	383**	---
NOVEMBER															
Norman Wells A	20.9	3.2	11.2	26.2	18.0	24.4	23.9	---	15*	54	125	86	117	114	---
Fort Simpson A	27.2	16.0	13.6	21.9	13.4	37.9	33.5	---	59	50*	81	49*	139	123	---
High Level A	27.9	21.3	19.1	15.0	35.9	12.7	48.2	---	76	68	54	129	46	173*	---
DECEMBER															
Norman Wells A	18.8	8.2	30.1	33.1	28.8	8.6	4.9	---	44*	160*	176*	153*	46*	26*	---
Fort Simpson A	23.5	7.9	15.1	21.7	20.1	26.1	8.2	---	34**	64*	92	86	111	35**	---
High Level A	24.7	9.2	18.9	19.1	18.8	14.4	15.2	---	37*	77	77	76	58	62	---
JANUARY															
Norman Wells A	19.5	---	14.0	18.5	15.1	14.5	16.8	19.7	---	72	95	77	74	86	101
Fort Simpson A	19.9	---	43.4	33.5	24.2	12.0	17.2	20.7	---	218*	168	122	60	86	104
High Level A	20.6	---	14.5	13.6	26.1	26.4	36.2	25.6	---	70	66	127	128	176*	124
FEBRUARY															
Norman Wells A	16.1	---	16.4	19.6	11.8	26.2	4.4	26.5	---	102	122	73	163	27	165
Fort Simpson A	19.0	---	42.7	42.6	6.9	23.4	18.8	3.8	---	225**	224**	36*	123	99	20**
High Level A	15.9	---	9.6	35.4	6.6	27.2	15.0	4.4	---	60	223*	42	171*	94	28*
MARCH															
Norman Wells A	12.9	---	5.6	7.0	13.1	3.9	11.8	20.0	---	43	54	102	30*	91	155
Fort Simpson A	21.7	---	13.3	3.2	44.7	13.9	17.7	13.6	---	27	15*	206*	64	82	63
High Level A	16.2	---	5.6	13.0	14.1	57.0	23.7	---	---	35	80	87	352**	146	---
APRIL															
Norman Wells A	15.4	---	6.9	23.0	14.2	14.6	5.4	4.0	---	45	149	92	95	35	26
Fort Simpson A	14.6	---	4.6	18.0	15.9	12.6	6.2	9.5	---	32	123	109	86	42	65
High Level A	17.4	---	4.3	6.0	11.2	12.3	26.9	---	---	25*	34*	64	71	155*	---

Source: Atmospheric Environment Service, Environment Canada, Monthly Record
Note: * = Difference > 1 Standard Deviation from Mean (68% significant)
** = Difference > 2 Standard Deviation from Mean (95% significant)

Table 3-1 (c): Winter climatic conditions 1983-1989: snowfall

Month/Station	Normal	Total Monthly Snowfall (cm) 1983	1984	1985	1986	1987	1988	1989	Difference From Normal (%) 1983	1984	1985	1986	1987	1988	1989
OCTOBER															
Norman Wells A	25.0	17.5	41.3	17.0	22.2	26.6	40.7	---	70	165	68	89	106	163	---
Fort Simpson A	18.5	24.6	36.2	41.8	12.2	17.9	41.6	---	133	196	226	66	97	225	---
High Level A	15.3	13.0	37.6	43.0	17.0	9.7	61.8	---	85	247	281	111	63	404	---
NOVEMBER															
Norman Wells A	21.3	3.2	13.1	29.8	18.0	40.6	32.2	---	15	62	140	85	191	151	---
Fort Simpson A	25.3	18.0	19.6	29.0	14.6	40.4	40.5	---	71	77	115	58	160	160	---
High Level A	29.1	21.7	22.3	17.1	42.2	15.8	54.4	---	75	77	59	145	54	187	---
DECEMBER															
Norman Wells A	19.3	10.3	36.8	38.6	38.0	10.8	8.3	---	53	191	200	196	56	43	---
Fort Simpson A	23.9	8.8	18.5	22.1	20.7	25.8	10.9	---	37	77	92	87	108	46	---
High Level A	30.9	12.4	21.7	20.1	20.2	17.1	22.7	---	40	70	65	65	55	73	---
JANUARY															
Norman Wells A	20.6	---	14.0	26.8	24.6	20.5	22.6	26.2	---	68	130	119	100	110	127
Fort Simpson A	20.7	---	39.5	40.4	34.2	12.4	19.8	22.0	---	191	195	165	60	96	106
High Level A	26.6	---	22.6	15.5	40.1	30.0	41.5	28.9	---	85	58	151	113	156	109
FEBRUARY															
Norman Wells A	17.3	---	17.3	24.4	18.2	27.2	4.6	34.6	---	100	141	105	157	27	200
Fort Simpson A	18.9	---	49.6	42.8	9.3	24.4	22.6	6.7	---	262	226	49	129	116	35
High Level A	20.6	---	14.8	39.2	7.4	29.7	16.2	7.4	---	72	190	36	144	79	36
MARCH															
Norman Wells A	13.6	---	5.6	8.3	17.7	4.6	14.8	32.6	---	41	61	130	34	109	240
Fort Simpson A	21.2	---	15.5	6.0	51.5	13.9	19.1	16.9	---	73	28	243	66	90	80
High Level A	21.0	---	7.2	13.6	16.3	60.5	24.4	---	---	34	65	78	288	116	---
APRIL															
Norman Wells A	15.3	---	6.0	23.2	15.8	18.5	8.2	6.0	---	39	152	103	121	54	39
Fort Simpson A	11.7	---	4.6	15.6	16.7	11.9	6.0	9.2	---	39	133	143	102	51	79
High Level A	14.5	---	1.8	2.0	2.8	2.4	21.3	---	---	12	14	19	17	147	---

Source: Atmospheric Environment Service, Environment Canada, Monthly Record.

Table 3-2 (a): Summer climatic conditions 1984-1988: air temperature

	Mean Daily Temperature (°C)						Difference From Normal (°C)				
Month/Station	Normal	1984	1985	1986	1987	1988	1984	1985	1986	1987	1988
MAY											
Norman Wells A	5.4	8.5	6.5	5.9	6.8	5.6	3.1*	1.1	0.5	1.4	0.2
Fort Simpson A	7.9	9.1	8.3	8.9	10.0	6.9	1.2	0.4	1.0	2.1*	-1.0
High Level A	9.3	8.2	9.5	9.9	9.8	8.4	-1.1	0.2	0.6	0.5	-0.9
JUNE											
Norman Wells A	14.0	16.5	14.3	14.8	14.9	15.7	2.5*	0.3	0.8	0.9	1.7*
Fort Simpson A	14.4	15.7	14.5	14.2	15.7	14.6	1.3*	0.1	-0.2	1.3*	0.2
High Level	13.6	14.2	13.6	13.1	14.2	14.2	0.6	0.0	-0.5	0.6	0.6
JULY											
Norman Wells A	16.3	15.3	14.0	17.1	17.1	16.2	-1.0	-2.3**	0.8	0.8	-0.1
Fort Simpson A	16.6	16.3	15.4	17.2	17.0	16.7	0.3	-1.2	0.6	0.4	0.1
High Level A	15.7	16.3	14.9	15.9	15.7	15.5	0.6	-0.8	0.2	0.0	-0.2
AUGUST											
Norman Wells A	13.4	12.9	12.2	13.2	12.5	14.7	-0.5	-1.2	-0.2	-0.9	1.3
Fort Simpson A	14.4	14.8	12.3	14.0	12.9	15.8	0.4	-2.1*	-0.4	-1.5*	1.4*
High Level A	14.0	15.4	12.0	13.7	12.2	14.3	1.4*	-2.0*	-0.3	-1.8*	0.3
SEPTEMBER											
Norman Wells A	6.1	6.0	7.2	7.4	8.0	5.2	-0.1	1.1	1.3	1.9*	-0.9
Fort Simpson A	7.3	6.5	7.7	8.4	10.2	7.2	-0.8	0.3	1.1	2.9*	-0.1
High Level A	8.1	6.2	6.4	7.8	10.0	7.5	-1.9	-1.7	-0.3	1.9	-0.6

Source: Atmospheric Environment Service, Environment Canada, Monthly Record.

Note: * = Difference > 1 Standard Deviation from Mean (68% significant)
** = Difference > 2 Standard Deviation from Mean (95% significant)

Table 3-2 (b): Summer climatic conditions 1984-1988: precipitation

	Monthly Total Precipitation (cm)						Difference From Normal (%)				
Month/Station	Normal	1984	1985	1986	1987	1988	1984	1985	1986	1987	1988
MAY											
Norman Wells A	17.0	32.0	28.6	16.4	21.0	25.4	188*	168	96	124	149
Fort Simpson A	31.1	5.2	15.6	16.2	4.5	64.8	17*	50	52	14	208*
High Level A	35.5	84.4	24.8	17.3	37.4	55.2	238**	70	49*	105	155*
JUNE											
Norman Wells A	37.0	48.9	52.5	21.7	30.2	63.8	132	142	59	82	172*
Fort Simpson A	38.7	59.3	31.6	48.0	34.6	174.4	153	82	124	89	451**
High Level	53.2	105.3	41.3	52.2	77.2	78.6	198*	78	98	145	148
JULY											
Norman Wells A	56.1	65.0	47.4	12.3	11.8	54.2	116	84	22*	21*	97
Fort Simpson A	59.3	103.0	65.2	41.3	26.2	87.2	174**	110	70	44*	147*
High Level A	68.9	61.8	63.3	80.8	66.7	35.8	90	92	117	97	52*
AUGUST											
Norman Wells A	58.6	43.7	20.7	47.6	48.6	21.8	75	35*	81	83	37*
Fort Simpson A	44.8	63.8	51.4	77.6	15.3	38.6	142	115	173*	34	86
High Level A	57.8	45.2	77.9	31.6	86.8	50.0	78	135	55	150	87
SEPTEMBER											
Norman Wells A	29.3	14.8	52.1	27.4	20.6	83.0	51	178*	94	70	283**
Fort Simpson A	31.3	11.4	14.3	31.0	36.3	19.9	36	46	99	116	64
High Level A	33.9	42.4	41.2	17.4	36.3	28.1	125	122	51	107	83

Source: Atmospheric Environment Service, Environment Canada, Monthly Record.

Note: * = Difference > 1 Standard Deviation from Mean (68% significant)
** = Difference > 2 Standard Deviation from Mean (95% significant)

deviation of the mean and 95% lie within two standard deviations of the mean.) The most significant aspects of climatic conditions with regard to terrain performance during the 1983-1989 period may be summarized as follows:

Air temperature:

Air temperature has fluctuated both above and below normal during the period October 1983 to April 1989. Both the high seasonal range of air temperatures within the pipeline corridor and the slightly warmer climate of Fort Simpson as compared to that of Norman Wells are shown graphically for the period 1984-1987 in Figure 3-1a. The diagram also suggests that a warming trend has occurred especially in winter temperatures over this period. This trend is highlighted in Figure 3-1b, which plots 12-monthly running mean annual temperatures. At both Norman Wells and Fort Simpson, there is evidence of an increase in mean annual temperature of approximately 2.0-2.5°C over the period. This may reflect long-term climatic warming, due to the effects of global environmental change; this interpretation is consistent with preliminary results of an ongoing EMR-Environment Canada climate change study. Analysis of existing air temperature data from meteorological stations in the Mackenzie Valley yield statistically significant increases up to 1°C in the past 50 years (A.S. Judge, personal communication). Alternatively, the trend may represent a more localized and short-term climatic phenomenon. In either case, the data emphasize that broader-scale environmental change must be taken into account when assessing the effects of project-specific terrain disturbance.

Snowcover:

Winter snowcover has been extremely variable throughout the period, as indicated by data recorded at Norman Wells and Fort Simpson Airports (Figure 3-2) and at the off right-of-way permanent snow depth markers installed at thermal fence sites in the fall of 1986 (Table 3-3). During the winter 1983-1984 construction period, air temperature was higher and snow depth lower than normal. Snowcover on December 31 ranged from 34 cm at Fort Simpson to only 9 cm at Norman Wells Airport. This contributed to problems of trafficability, particularly on northern sections of the right-of-way. Above normal temperatures in March 1984 also led to an early disappearance of the snowcover. By contrast, the 1984-1985 winter construction season was characterized by near normal snowcover.

Summer precipitation:

Summer precipitation is frequently associated with discrete storm events. The high degree of both temporal and spatial variability of such events is illustrated by graphs showing the daily rain distribution at Norman Wells and Fort Simpson in summer

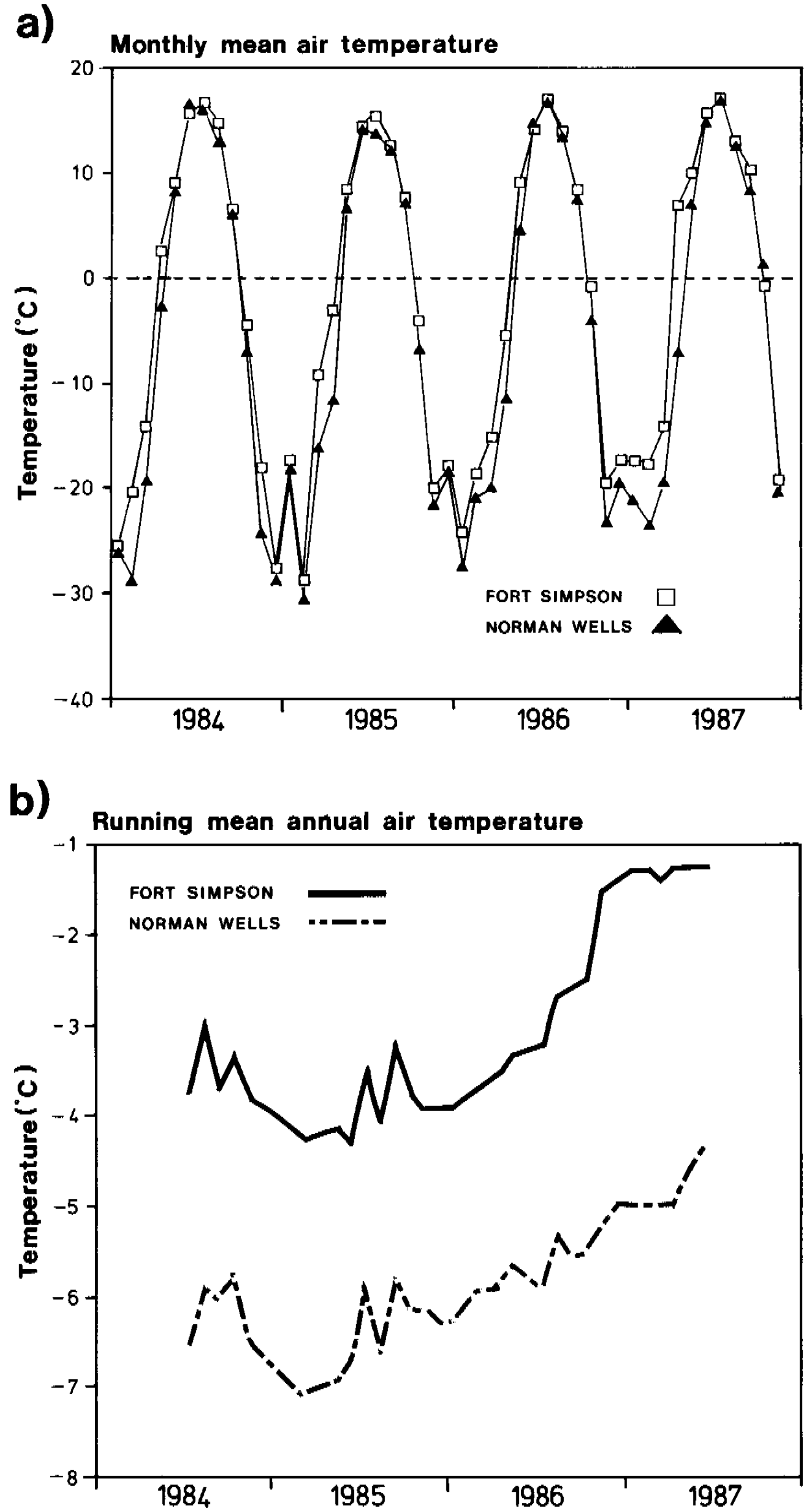


Figure 3-1. Monthly mean and running mean annual air temperatures at Norman Wells and Fort Simpson AES weather stations (1984 to 1987).

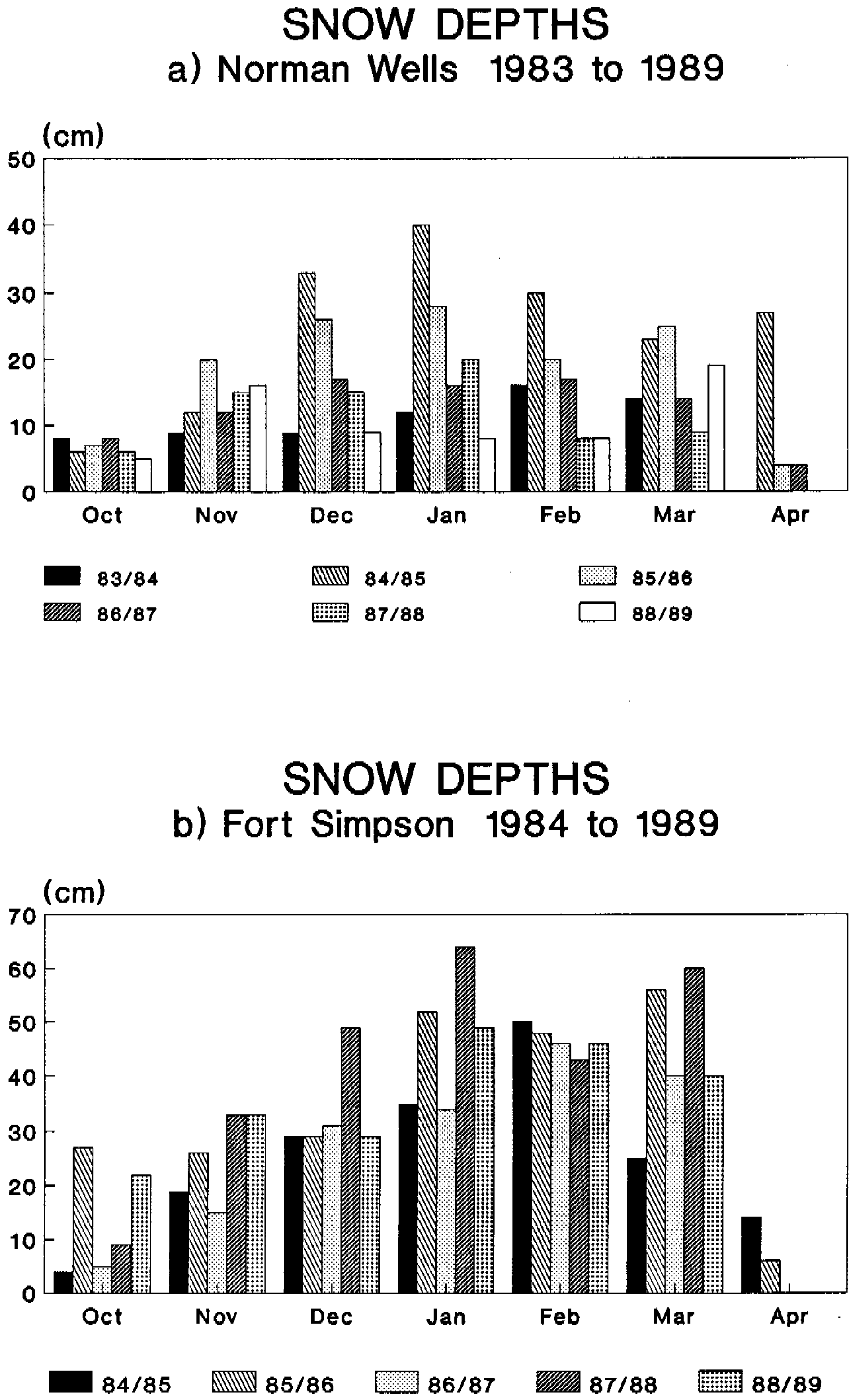


Figure 3-2. Depth of snowcover recorded at AES stations in Norman Wells (1983-1989) and Fort Simpson (1984-1989).

TABLE 3-3. March snow depths at permanent snow depth markers adjacent to the Norman Wells Pipeline right-of-way.

SITE	KM	1987		1988		1989	
		cm	(date)	cm	(date)	cm	(date)
84-1	0.0	50	(14/3)	30	(10/3)	70	(13/3)
84-2a	18.9	58	"	45	"	88	(14/3)
84-2b	19.3	55	"	35	"	80	"
84-2c	19.6	50	"	30	"	100	"
84-3a	79.2	80	(10/3)	45	"	120	"
84-3b	79.3	55	"	25	"	43	"
85-7a	271.2	55	"	45	(9/3)	65	(15/3)
85-7b	272.0	55	"	45	"	55	"
85-7c	272.3	70	"	60	"	76	"
84-4b	478.1	60	"	n/a	"	60	(16/3)
85-8a	557.8	25	"	40	(8/3)	35	"
85-8b	558.2	40	(11/3)	55	"	48	"
85-8c	558.3	40	"	50	"	53	"
85-9	583.3	50	(12/3)	55	"	54	"
85-10a	588.3	40	"	55	"	40	"
85-10b	588.7	40	"	60	"	55	"
85-11	597.4	55	"	72	(7/3)	57	(17/3)
85-12a	608.6	60	"	74	"	65	"
85-12b	608.7	50	"	66	"	50	"

1988 (Figure 3-3). The right-of-way surface is particularly vulnerable to erosion caused by high intensity precipitation during the first summer following construction. In summer 1984, precipitation was well above normal, resulting in high levels of surface runoff and contributing to surface erosion of the right-of-way. Below normal precipitation through much of summer 1985 probably contributed to a generally lower frequency of erosion conditions on both 1983/84 and 1984/85 construction spreads. The extremely wet summer of 1988 (Fort Simpson precipitation was 200% of normal in May, 450% of normal in June and 150% of normal in July) also resulted in some surface erosion.

Major summer storm events also result in high runoff levels in streams and rivers. For example, in June 1986 the Wrigley area received approximately 56 mm of rainfall in 24 hours (recorded at the Mt. Gaudet fire tower). This resulted in high flood discharge within the Hodgson Creek catchment, and erosion of the pipeline crossing. In July 1988, the same area received approximately 63 mm of rainfall during a single storm, resulting in further damage to the Hodgson Creek crossing and erosion of the Ochre River crossing. Details of the June 28th to July 2nd, 1988, storm in the Mackenzie area are available in Westerman and Burke (in prep).

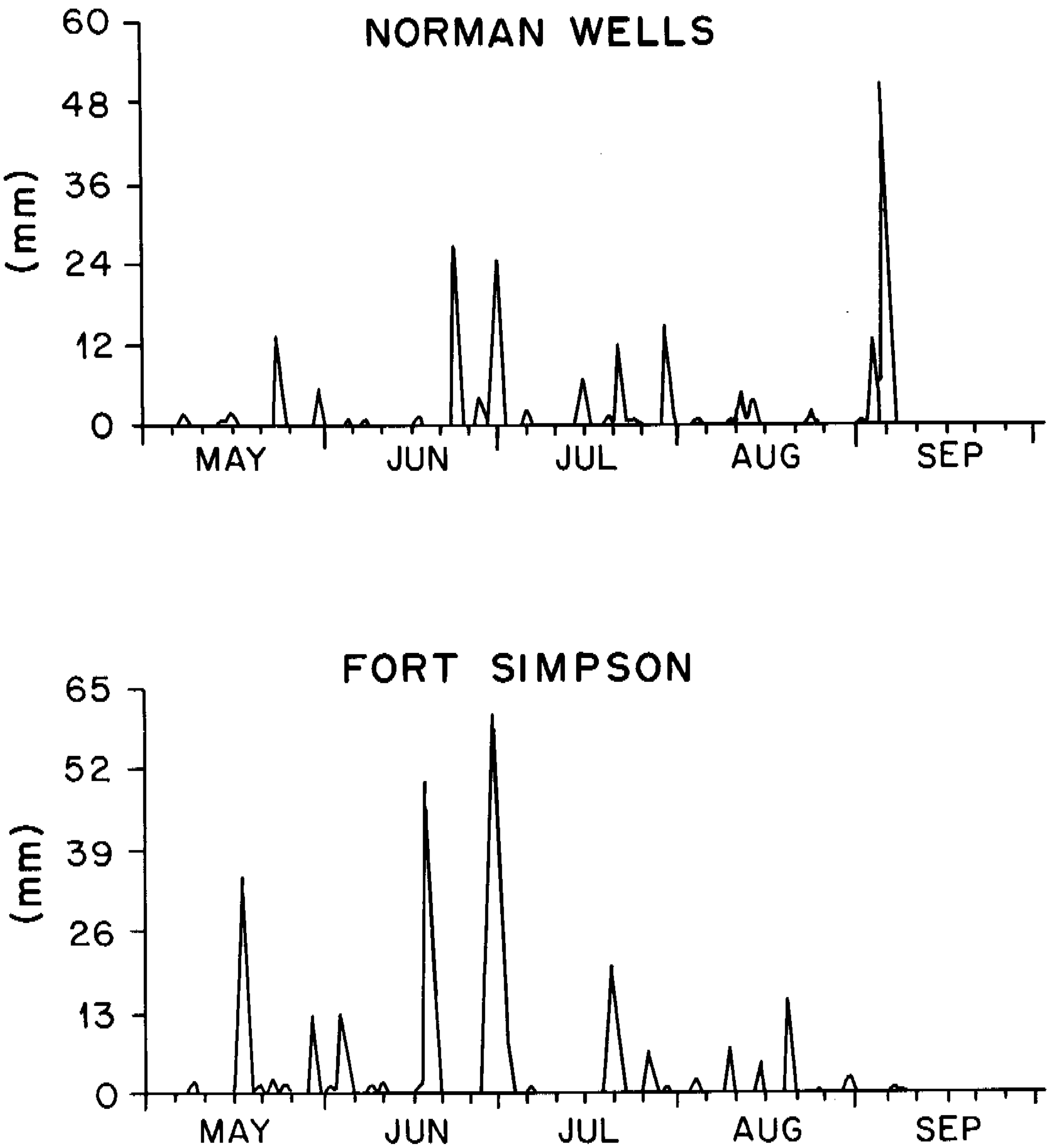


Figure 3-3. Daily rain distribution at Norman Wells and Fort Simpson (summer 1988).

4. SITE SYNTHESIS (1984-1987)

Instrumented monitoring sites were established to evaluate the thermal and environmental effects of the small, buried, uninsulated pipeline in warm and discontinuous permafrost, and to investigate the terrain response to particular pipeline design features and mitigative measures. Pipeline design concepts and mitigative measures are reviewed in Chapter 3 of Volume I; construction and operations details are reviewed in Chapter 4 of Volume I. The regional environmental framework (climate, permafrost and terrain) for the pipeline is described in Chapter 2 of Volume I.

The permafrost and terrain encountered along the route (Kay et al. 1983) required specialized design and mitigative approaches to minimize terrain disturbance and ensure pipe safety under conditions of thaw settlement, frost heave or slope instability. Briefly, features selected to limit energy exchange with surrounding soils included: 1) pre-construction winter right-of-way (ROW) clearance, maximizing the use of previous cutlines, 2) winter construction using temporary roads, 3) shallow pipe burial depth (average 1 m), 4) small diameter (324 mm) generally uninsulated pipe, 5) chilling of the oil to near 0°C before pumping at Norman Wells for pipeline operation at "ambient" ground temperature, and 6) wood chip insulation of thaw-sensitive slopes.

A small diameter line and the chilling of the oil at Norman Wells were features designed to minimize heat input from the pipeline into the surrounding terrain. The pipeline was not expected to cause significant thawing of underlying frozen ground. By contrast, clearing of the right-of-way and construction activities were expected to cause permafrost to slowly degrade beneath the right-of-way because of changes to the ground thermal conditions resulting from the removal, disturbance or changes to vegetation and the insulating surface organic layer.

The pipe and ground thermal regimes are key to the evaluation of thaw settlement and frost heave design and mitigation. Thaw depth predictions are central to IPL's thaw settlement design and mitigation. Thaw depths also affect surface and subsurface geomorphic processes and hydrology, and the stability of thaw-sensitive slopes. Differential thaw settlement occurring at terrain transitions was of particular concern for pipeline stability. Surface settlement may be used as an indicator of possible thaw settlement beneath the pipe. It also affects surface drainage, ponding and erosion, and select backfill requirements.

This chapter focuses on pipe temperatures, pipe-ground temperature comparisons, active layers and thaw depths, as well as surface change and thaw settlement in order to evaluate the thermal behaviour of the pipeline and the thaw settlement design. The discussions emphasize the general results and trends obtained at the 23 instrumented thermal fences from 1984 to 1987.

Results are compared whenever possible to the expected or predicted responses outlined by IPL during the project's conceptual and final design and assessment phases. Additional observations and analyses are discussed Burgess (1988), Burgess and Harry (1988), Burgess et al. (1986), and Burgess and Riseborough (1989).

4.1 PIPE TEMPERATURES (1984-1987)

The selection of a small diameter pipeline buried at a shallow depth and the chilling of the oil to near 0°C at its point of entry are features designed to (1) limit the thermal input of the pipeline to the surrounding terrain, (2) minimize terrain disturbance, and (3) ensure pipe integrity. According to the pipeline design, little thaw of underlying permafrost is expected due to the temperature of the pipe; thaw is expected due to ROW surface disturbance (clearing, construction, maintenance).

These pipe thermal characteristics have led to the description of the Norman Wells pipeline as operating at "ambient ground temperature" (NEB, 1981: Chapter 7, Environmental Matters, 7.3 Terrain, p.77-78). The use of "ambient" serves to readily distinguish the small diameter oil pipeline from a hot oil line, such as the larger diameter (122 cm, 48 inch) and hot (38° to 63°C, 90 to 145°F) Trans-Alaska Pipeline (Chapter 5, Vol.I). Several elaborations or interpretations of the "ambient" concept have been given:

"...the temperature of the pipeline would always be close to the ambient ground temperature..." (IPL, 1980: Geothermal Analysis, p.16),

"...the pipe will therefore be buried in the active layer of the ground and for much of its length will overlie permafrost. Since the pipeline is designed to operate at ground temperature, the temperature of the pipeline is expected to follow that of the surrounding soil." (Duffy, 1981: section 4.2.1), and

"...the temperature of the pipeline would be controlled by adjacent ground temperatures..." (NEB, 1981: section 5.2.3., Geothermal Analysis, p.40),

"Close" was generally not defined in the above reports, although mention is made in the first reference quoted above of "...close (within a very few degrees) to the temperature of the surrounding ground..." (p.17 Geothermal Analysis, IPL, 1980). More recently (IPL, personal communication 1988), this has been defined as being within 3 to 5 K (see Table of Abbreviations) of the surrounding ground temperature.

A first step in verifying the ambient behaviour is to determine the actual temperature of the pipe and to compare this to predicted values; this is the subject of the sub-sections 4.1.1 to 4.1.4. A second step, involves an examination of actual pipe temperatures in relation to the surrounding ground temperatures, both on and off the ROW; this analysis follows in section 4.2. These analyses and comparisons are of interest in both "thaw-stable" and "thaw-sensitive" terrain.

The pipeline system consisting of three pump stations started operation in April 1985. Oil is chilled at the ESSO facilities before delivery to IPL. In 1986 IPL installed in line thermocouples to monitor oil temperature upon entry and exit from each pump station (only one thermocouple, the entry recorder at Norman Wells, had been in place since start-up). During the first year of operation, the oil was chilled on average to about -2°C (Pick, 1986); during the second year the delivery temperature dropped to approximately -5°C. The outgoing oil temperature at Pump Station 1 is generally about 3 degrees warmer than the incoming oil (after chilling, before pumping) (IPL, pers. comm. 1988). The average amount of oil moved from Norman Wells was about 21,700 b/d during the first year of operation and 23,700 b/d during the second year of operation (see Table 4-6, Volume I); these years were both below the design capacity of 30,000 b/d.

The temperature instrumentation at most thermal fences includes five sensors placed on the outside of the pipe (as shown in Figure 2-2). The average depth of cover over the pipeline, excluding roach, was initially about 0.9 m (Wishart, 1988); individual values for each thermal fence are listed in Table 4-1, and range from 0.77 to 1.0 m, based on measurements of frozen backfill. Table 4-1 also lists pertinent information from each fence such as:

i) soil type down to one metre,
ii) presence or absence of permafrost,
iii) an estimate of whether the burial of the pipe was within the initial post-construction active layer of the ROW , partially in permafrost, completely in permafrost, or within the seasonal frost layer (based on the first summer's temperature data).

Baseline data on depth of active layer prior to clearing or prior to construction was not available, one of the disadvantages of not having any instrumentation in place prior to construction.

The thermal fences have first been divided into two groups for a general discussion of the pipe temperature data. The northern

TABLE 4-1. Pipe burial information - instrumented sites.

1 FENCE	2 KP	3 GROUND THERMAL REGIME	4 CLEARING DATE	5 DEPTH OF COVER(M)	6 PIPE IN ACTIVE LAYER?	7 DITCH SOIL TYPE	8 ROACH BACKFILL COMMENTS
84-1	0.02	pf	82/83	0.90	partly	clay till	native
84-2A	19.0	pf	1960's	0.95	yes	silty clay	native
84-2B	19.3	pf	1960's	1.00	partly	silty clay	native
84-2C	19.6	pf	1960's	0.95	yes	clay till	native
84-3A	79.2	pf	83/84	0.90	partly	peat/ice	native
84-3B	79.4	pf	83/84	0.85	partly	peat/sand	native
85-7A	271.2	pf	1960's	0.90	partly	peat/clay	select
85-7B	272.0	pf	1982	0.90	yes	peat/clay	select
85-7C	272.3	pf	83/84	0.90	partly	peat/clay	native
84-4A	478.0	uf	82/83	0.90	no (sf)	silt/sand	native
84-4B	478.1	uf	82/83	0.90	no (sf)	sand	native
85-8A	557.8	pf	83/84	0.90	yes	peat/sand	native
85-8B	558.2	pf	83/84	0.90	partly	peat	native
85-8C	558.3	pf	83/84	0.90	partly	peat	native; remedial silt backfill in 1986
85-9	583.3	uf	83/84	0.90	no (sf)	silty gravel	native
85-10A	588.3	uf	1982	0.95	no (sf)	peat/sand	native
85-10B	588.7	pf	83/84	0.97	partly	peat	native
85-11	597.4	pf	1982	0.95	yes	peat/sand	native; remedial gravel backfill in 1986
85-12A	608.6	uf	83/84	0.95	no (sf)	peat	native
85-12B	608.7	pf	83/84	0.95	partly	peat	native
85-13A	682.2	pf	83/84	NA	NA	peat	native
85-13B	682.4	pf	83/84	NA	NA	peat	native
85-13C	682.6	uf	83/84	NA	NA	peat	native
84-5A	783.0	pf	82/83	0.77	partly	peat	native
84-5B	783.3	pf	82/83	0.85	partly	peat	native
84-6	819.5	pf	82/83	0.80	partly	peat	native

Notes:

Column 1	first two digits of site number refer to year established
Column 2	KP = kilometre post
Column 3	pf = permafrost at site at time of establishment uf = unfrozen, no permafrost at time of establishment
Column 5	depth of pipe cover, at time of burial, excluding roach
Column 6	Comments on active layer are based on temperature data from the first thaw season after site establishment: yes = pipe entirely within active layer partly = pipe partially in active layer/permafrost or entirely in permafrost no (sf) = pipe within seasonal frost layer of an unfrozen site
Column 7	description of soil type to bottom of ditch
Column 8	nature of original backfill and remedial backfill if present
NA	info not recorded, no pipe thermistors installed

group includes fences between km 0 at Norman Wells and km 272, north of Wrigley, N.W.T., ie. between Pump Station 1 and Pump Station 2 (kmp 336.). The southern group includes fences between km 477 north of Fort Simpson, N.W.T. and km 818 in northern Alberta; it also includes the third Pump Station at km 586. This northern/southern division corresponds roughly to the transition from widespread to sporadic discontinuous permafrost.

4.1.1 Northern Section (km 0 to 272)

Permafrost underlies about 75% of the terrain and all of the 9 thermal fences in this section (see Volume I, Chapter 2, for background information on permafrost conditions along the pipeline route). Monthly pipe temperatures recorded manually from 1984 to March 1987 at all fences from km 19 to 272 fall within the ranges plotted in Figure 4-1. Data from the fence at Norman Wells, km 0.02 will be discussed separately due to its proximity to the chilled source.

The five fences established in 1984 have up to one year of pipe temperature data prior to the presence and flow of oil in the line. "Leave to open" the pipeline was granted by NEB on April 17, 1985 and this date is indicated with an arrow on Figure 4-1. Data collected before and after this date are designated pre-flow and post-flow respectively. Pre-flow pipe temperatures show a wider range and larger annual amplitude than post-flow.

The diversity of the adjacent ground thermal regimes is reflected in the range of the pre-flow data. This is demonstrated by Figure 4-2 in which the pipe temperatures at the three fences at site 84-2, Canyon Creek (km 19), are plotted. Temperature measurements are taken an average of once a month, however, the data are drawn as continuous lines rather than as discrete points for ease of comparison. For convenience results from only one of the sensors is plotted for each fence, since the pipe temperatures recorded at a site generally differ by less than a degree amongst the five sensors, as shown for example in Figure 4-3. Note in Figure 4-2 that differences of up to 8 degrees were observed between the Canyon Creek fences before flow, whereas after flow pipe temperatures are similar at all three fences. Distances of 300 m separate fence A from B, and B from C.

The different pre-flow pipe temperatures at each of the Canyon Creek fences reflected the difference in their respective surrounding soil temperatures. Hence the pipe temperatures were distinct from one fence to the next. (Fence 84-2A is located on level terrain in an ice-poor till, fence 84-2B is located on an east facing wood chip insulated slope, while fence 84-2C is located on the uninsulated west-facing slope on the southern side of Canyon Creek). Appendix C provides individual plots comparing pipe

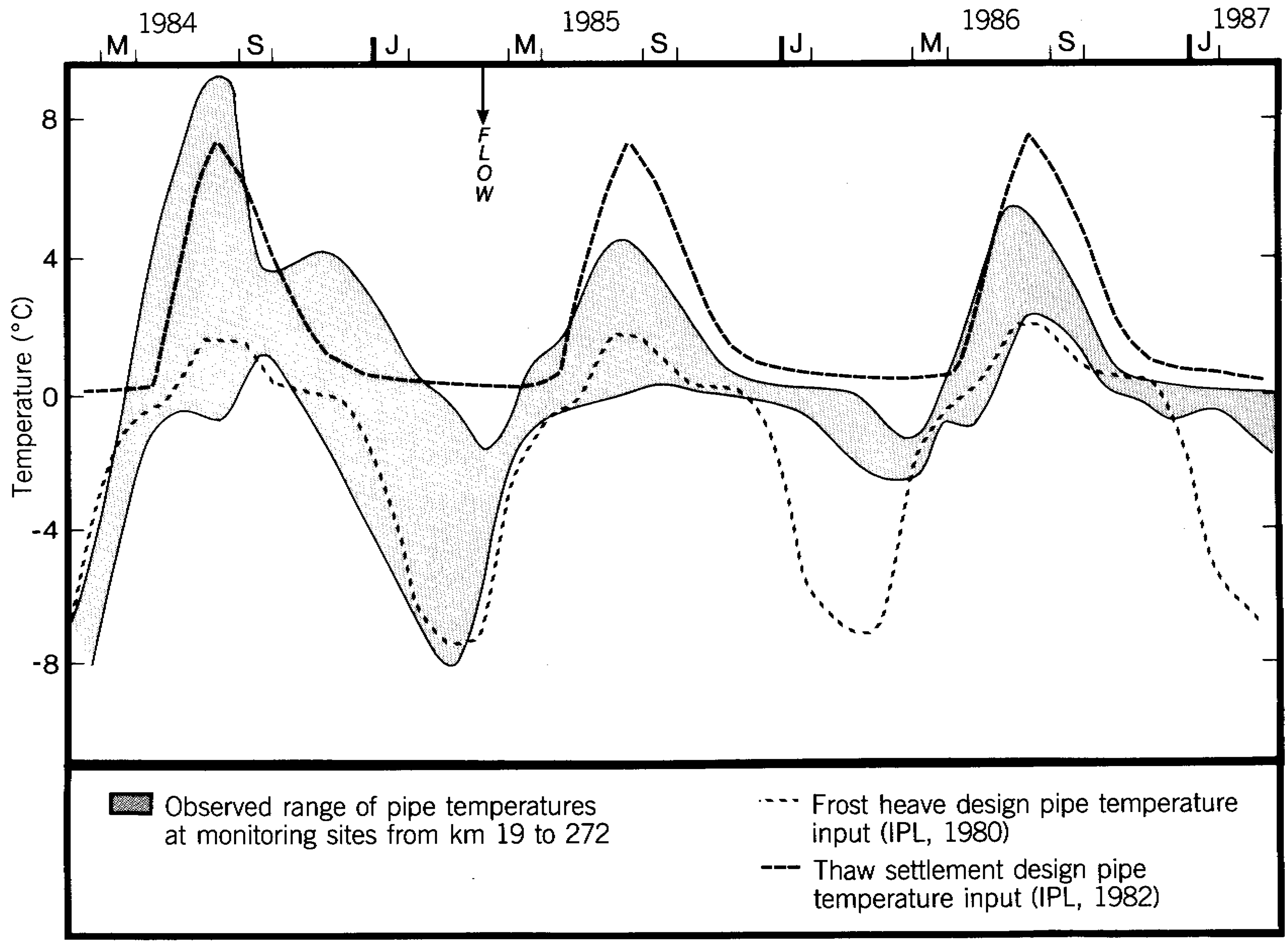


Figure 4-1. Observed range of pipe temperatures at monitoring sites from km 19 to km 272 (April 1984 to March 1987) and IPL design pipe temperature curves.

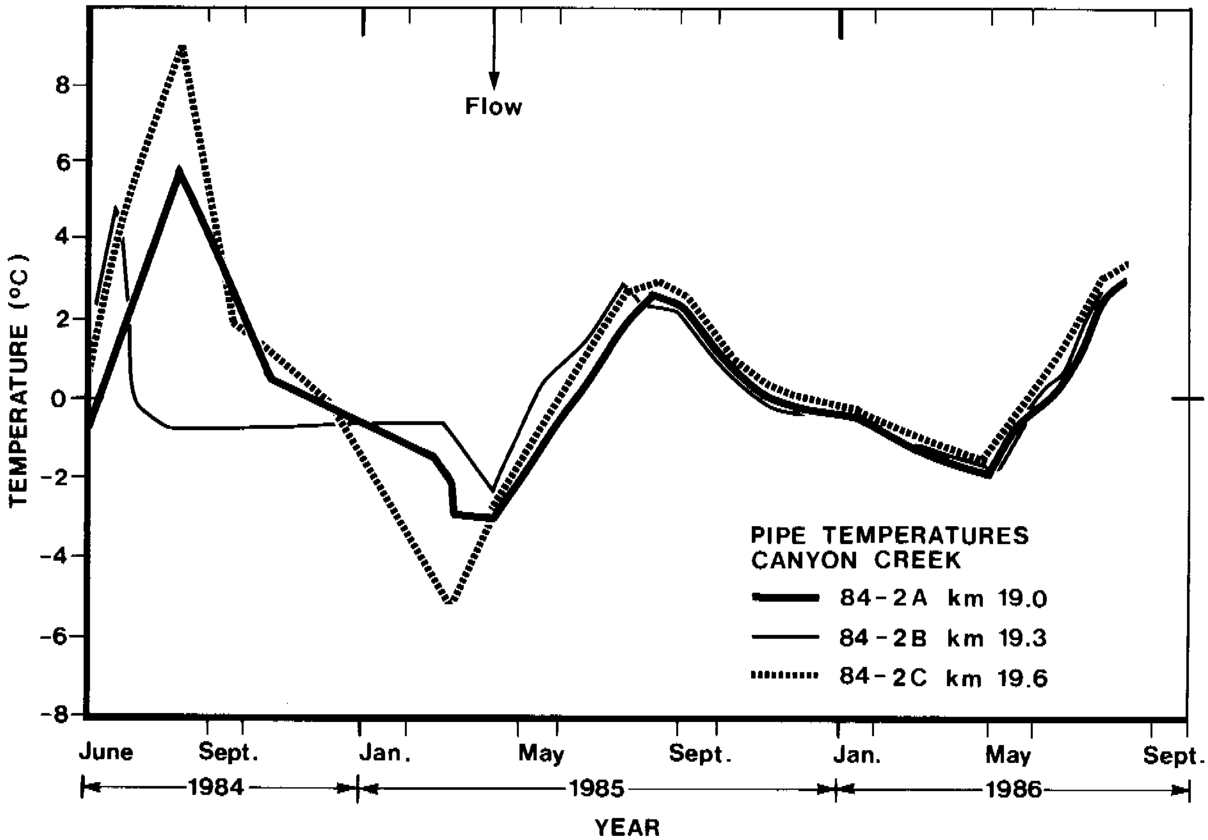


Figure 4-2. Pipe temperatures recorded at the three thermal fences at site 84-2 Canyon Creek (one sensor plotted from each fence).

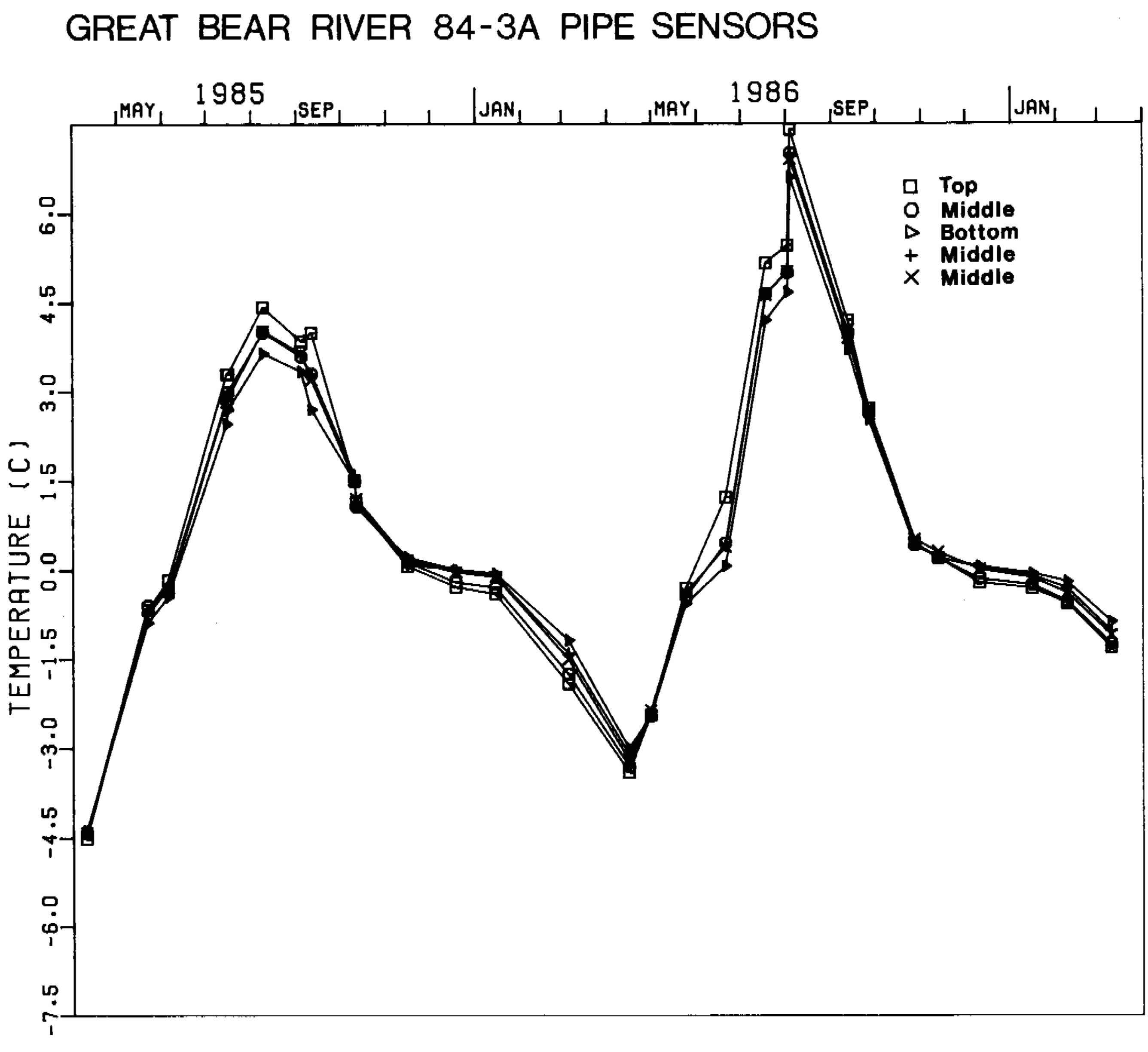


Figure 4-3. Pipe temperatures recorded by all 5 sensors at thermal fence 84-3A Great Bear, km 79.2.

temperatures and ground temperatures recorded on the ROW, several metres away from the trench, for each fence. Post-flow pipe temperatures at each fence differ from their respective surrounding soil temperatures; differences of 2 to 4 degrees are commonly observed in the plots in Appendix C. The post-flow pipe temperatures are however similar at the three fences (Figure 4-2).

The post-flow pipe temperature data from the Canyon Creek fences indicate that the length scale required for the operating pipeline to come into equilibrium with adjacent ground temperatures is much greater than the scale of spatial variation of the ground thermal regimes at this site. Pre-flow temperatures on the external pipe wall flow were thus governed by the surrounding soil at each fence, whereas post-flow temperatures are also partially controlled by the flowing oil and most likely represent the interaction of the average adjacent soil temperature over the first 20 km of the pipeline with the chilled oil.

Both Figure 4-1 and Figure 4-2, also demonstrate clearly the warmer winter pipe temperatures observed since oil began flowing. The pipe temperatures at all these northern fences clearly follow an annual freeze/thaw cycle. This seasonal thawing and complete freezeback would suggest that frost heave due to a permanent frost bulb is not a concern from km 19 to km 272.

Site 84-1

Monthly pipe temperatures recorded from the five sensors at site 84-1, km 0.02, immediately downstream from Pump Station 1 show fluctuations after start-up (Figure 4-4). These variations do not follow an annual variation similar to the ground thermal regime; they reflect variations in pressure (flow rate) or chiller delivery temperature and periods when the line was inoperative (for example June 1986 reading). Fluctuations in oil temperature at Pump Station 1 occur especially during changes or malfunctions in the Esso Resources' chillers when warm oil, such as that used to flush waxes from the chillers, has been pumped down the pipeline. These fluctuations have been damped at site 84-2 (km 19); pipe temperatures at site 84-2 fences, as shown in Figure 4-2, follow a typical seasonal cycle.

Figure 4-4 shows a general decrease in pipe temperatures at site 84-1 from the first to the second year of operation. This decrease is primarily a gradual response to operational changes (e.g. increased pump efficiency, more rapid shutdown by IPL if oil delivery temperature criteria are not met, modifications to ESSO's chillers) which combined to reduced oil output temperatures. Mean annual pipe temperatures (discussed further in section 4.1.3) at thermal fence 84-1 dropped from 0.6°C to -0.2°C between the first and second year of operation.

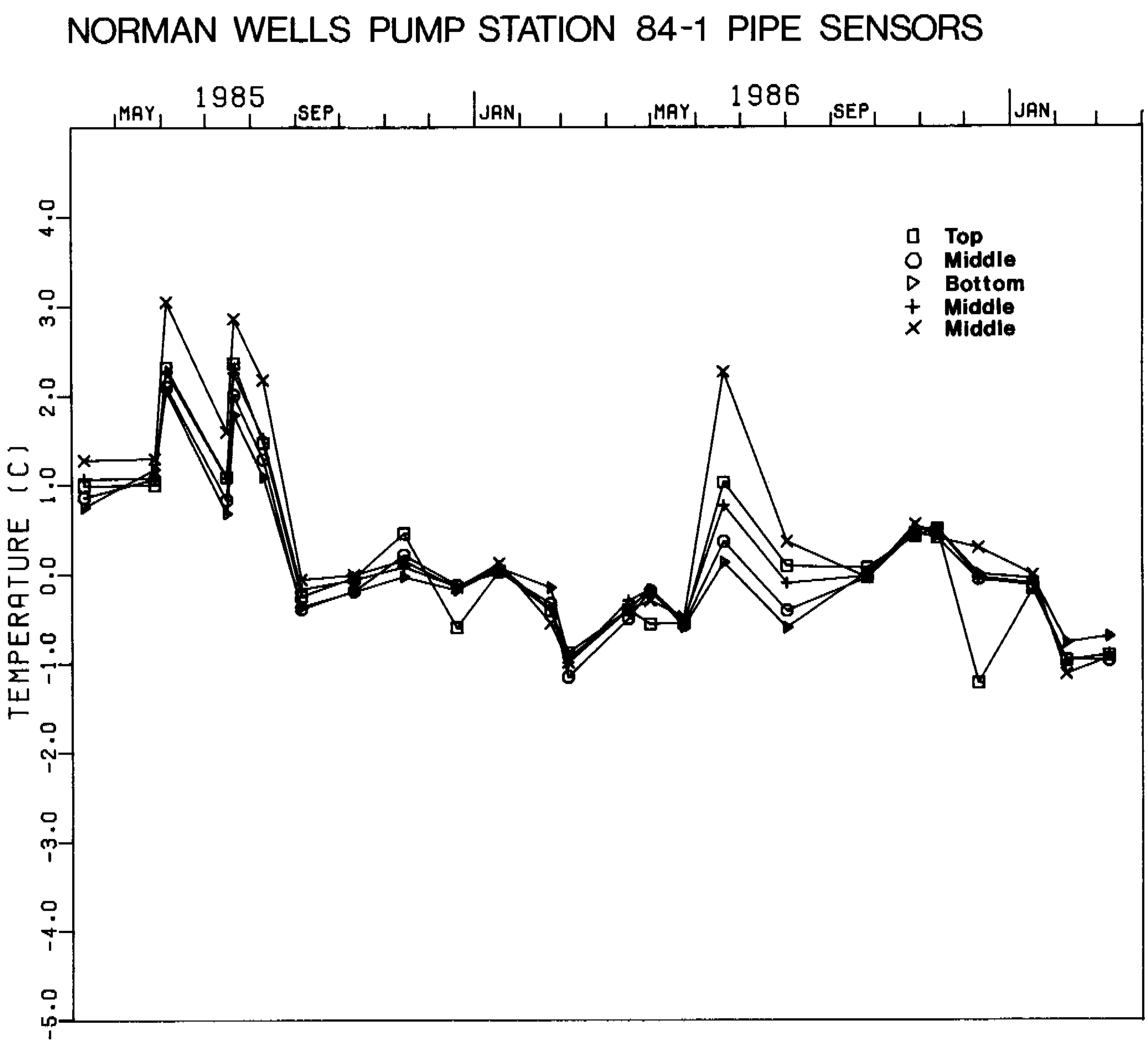


Figure 4-4. Pipe temperatures recorded by all 5 sensors at site 84-1 since pipeline operation began to March 1987.

4.1.2 Southern section (km 477 to 818)

In the southern section permafrost underlies approximately 25% of the terrain with numerous frozen/unfrozen interfaces, reaching as many as 15 per km (Kay et al., 1983). This section includes thermal fences downstream from the Wrigley Pump Station (km 336), and up and downstream from the Mackenzie Pump Station (km 585). The range of pipe temperatures recorded at the 14 fences located in this portion of the route are plotted versus time in Figure 4-5. Pre-flow temperatures are not shown since most sites were established in 1985 and only sparse data were gathered at the few 1984 sites. Individual plots for each fence are shown in Appendix C.

Winter pipe temperatures have again been conspicuously warmer since the pipeline commenced operation; in fact pipe temperatures rarely fall below 0°C at these southern thermal fences. Pipe temperatures remain positive year round at many sites (5A, 5B, 6, 10A, 10B, 11, 12A, 12B), while at the remaining fences (8A, 8B, 8C, 9) pipe temperatures fall slightly below 0°C (i.e probably not below the freezing point depression of the surrounding soils). All monitoring fences, nine of which were originally underlain by permafrost, have mean annual pipe temperatures well above 0°C (see section 4.1.3).

Although fence 85-9 (km 583.3) and fence 85-10A (km 588.3) are located only 5 km apart, pipe temperatures are consistently 2 to 3 degrees warmer at 10A (Figure 4-6). Ground temperatures on the other hand do not similarly increase (compare plots for each fence in Appendix C). The increase in pipe temperature likely reflects the increase in oil temperature during the pumping process at Pump Station #3 located between these two fences. Under stable line conditions a temperature increase of about 3.5°C occurs across this station (IPL, pers. comm.). Pipe temperatures at fence 85-12A, located another 20 km to the south, are plotted in Figure 4-6 and are also warmer than pre-pump station values. These observations suggest that more than 20 km are required to dissipate the heat gained during pumping.

4.1.3 Mean annual pipe temperatures

Mean annual pipe temperatures (average of the 5 pipe sensors) have been calculated for each thermal fence. These calculations involved curve fitting (using cubic spline interpolation) to the temperature data plotted versus time, in order to generate regularly spaced points - in this case weekly interpolated values - from which mean annual values can be readily determined (details on the technique are given in Riseborough et al., 1988).

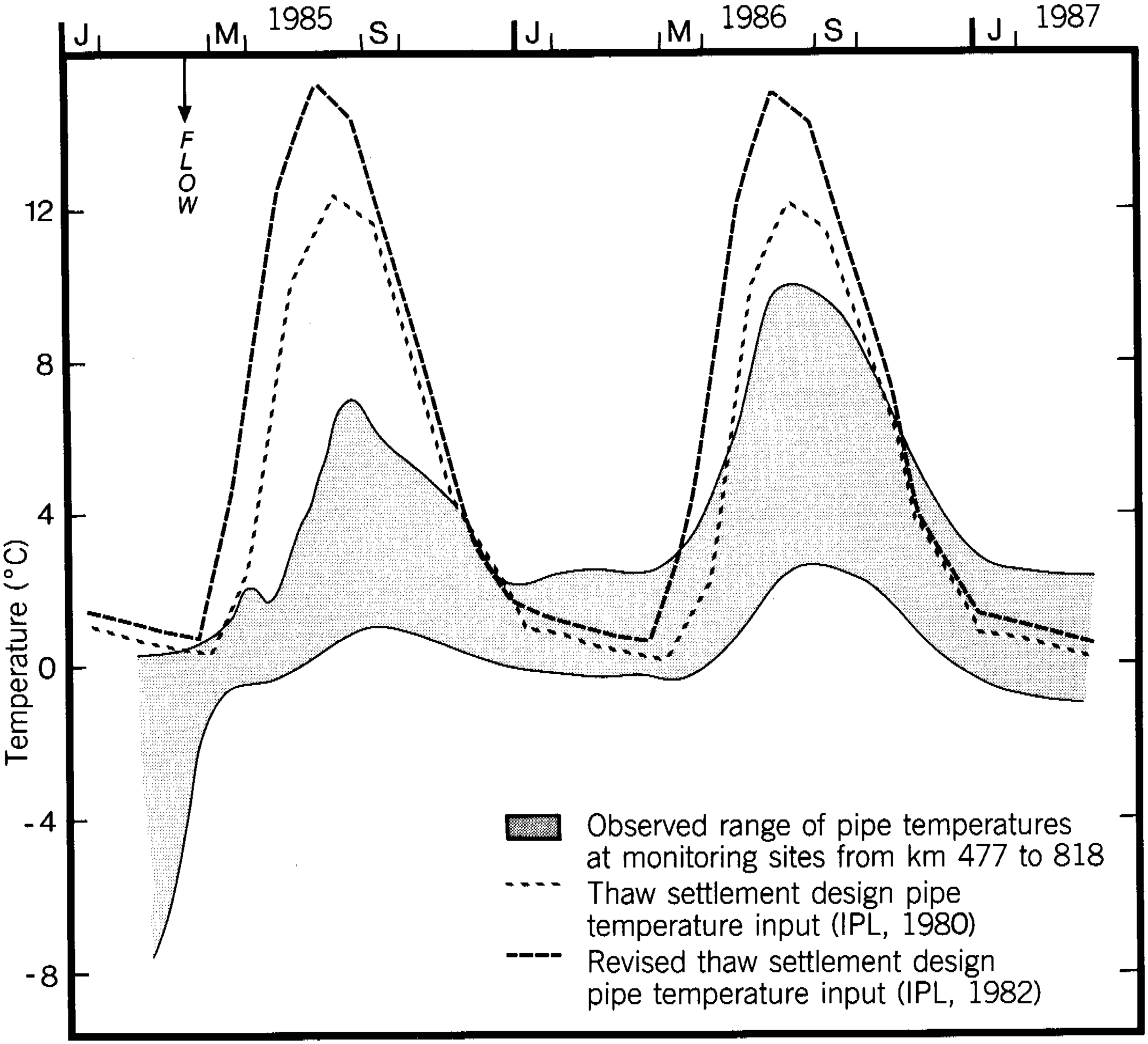


Figure 4-5. Range of pipe temperatures recorded at southern monitoring sites, km 477 to 818, from 1985 to 1987.

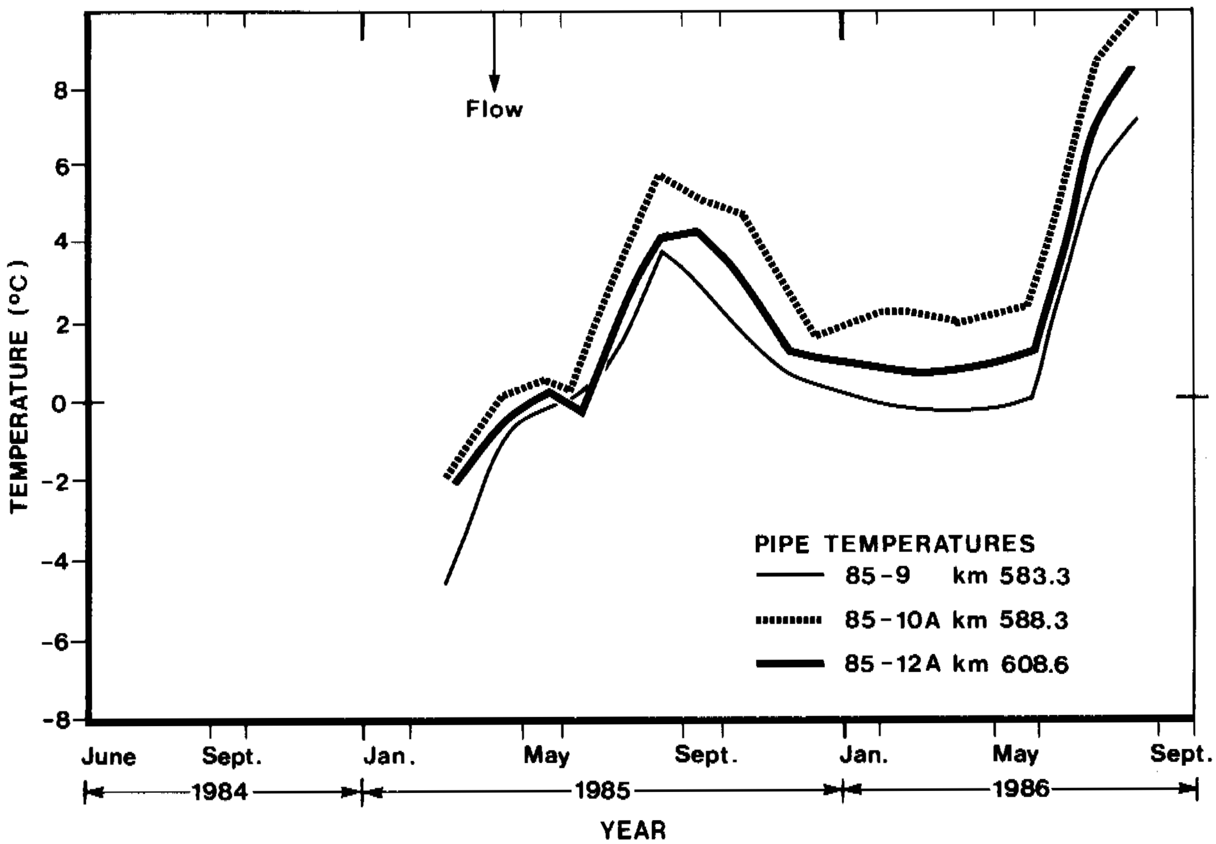


Figure 4-6. Comparison of pipe temperatures before (fence 85-9, km 583.3) and after (fence 85-10A, km 588.3) Pump Station 3.

Since calculation of a mean annual temperature removes the seasonal variability (as illustrated, for example, in Figure 4-7 for fence 85-8A), running mean annuals serve as useful tools to examine long term trends in pipe temperature.

In general (3/4 of sites), pipe temperatures warmed during the first two years of operation, but the rate of warming has been decelerating. The trends revealed by these running means are discussed in more detail in the section on pipe/ground temperature comparisons (section 4.2).

Mean annual pipe temperatures for the first year of operation (April 1985 to March 1986) and for the second year of operation (April 1986 to March 1987) are plotted versus kilometrepost along

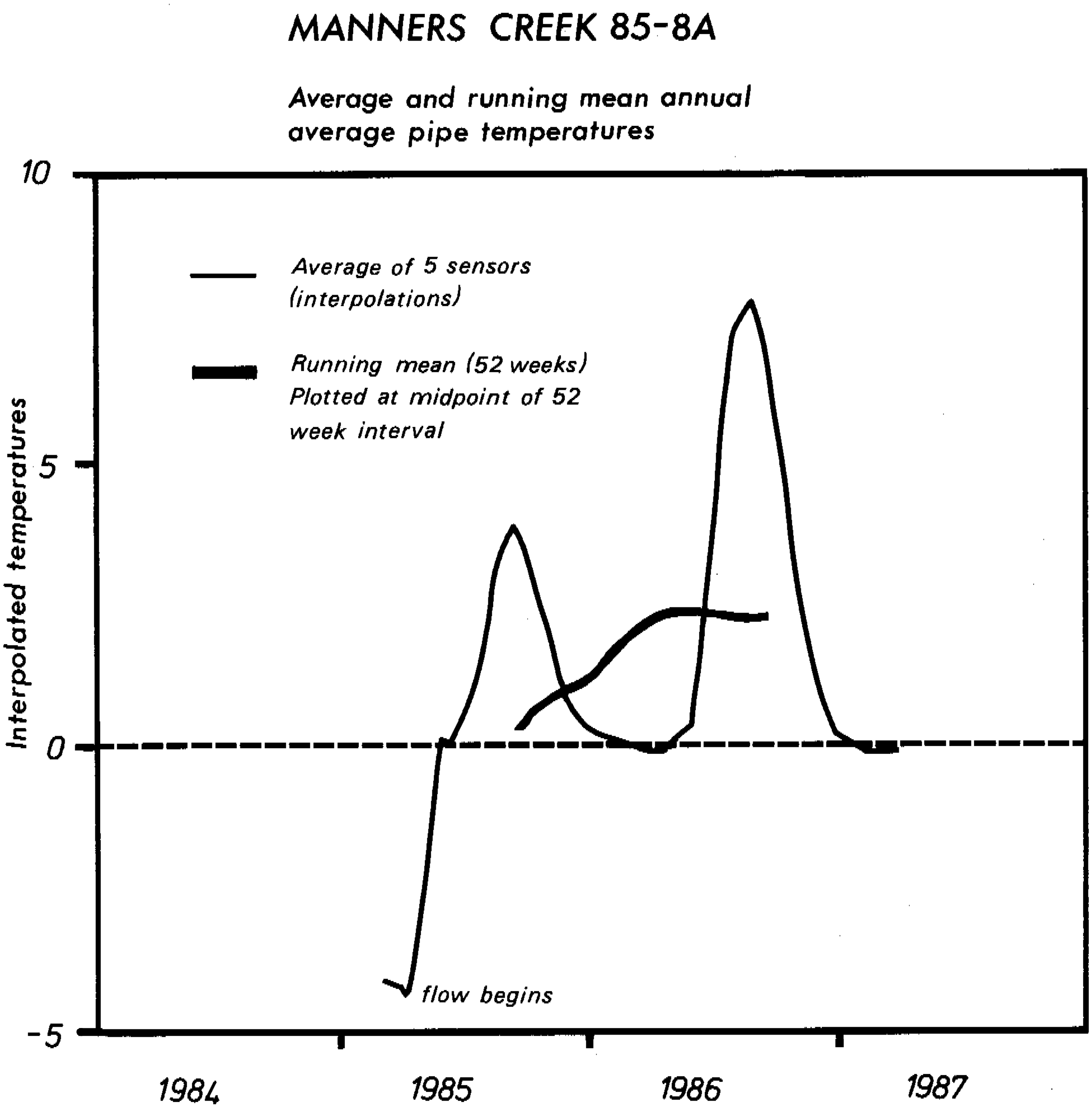


Figure 4-7. Example of average interpolated pipe temperature versus time and calculated running mean annual pipe temperature, 85-8A, km 557.8.

the pipeline route in Figure 4-8. Several features are evident on this plot: 1) the general trend of increase in mean annual pipe temperature from the first to second year of operation at most sites, 2) the general north to south increase in mean annual pipe temperature, 3) the >0°C mean annual pipe temperature of the "ambient" line, both within predominantly frozen and unfrozen terrain (with the exception of site 84-1 where mean temperatures are now below 0°C due to the drop in input temperature as discussed in section 4.1.2); mean annual pipe temperatures ranged from -0.3 to +5°C following two years of operation, 4) the 2 degrees increase in pipe temperature following pumping without refrigeration at Pump Station 3. The <0°C mean annual temperatures at site 84-1 suggest that frost heave due to a permanent frost bulb around the pipe may be a possibility at this site and near the start of the pipeline.

4.1.4 Observed and predicted pipe temperatures

Pipe temperature curves used by IPL as input in their two dimensional geothermal simulations to determine frost penetration and thaw depths beneath the pipe and right-of-way are shown in Figure 4-1 for the northern portion of the route. The lower curve represents the coldest pipe thermal regime expected for frozen ground, with a mean annual temperature of -2°C, and was used to model frost penetration for frost heave design (IPL, 1980). The upper curve represents the warmest pipe thermal regime expected in disturbed unfrozen terrain in "region 14" (permafrost region from km 0 to 110, used by IPL in their geothermal analysis, see section 2.3.2 in Volume I or IPL, 1982f) with a mean annual pipe temperature of +2°C and was used to model maximum thaw depths for thaw settlement design.

It should be mentioned that the approach taken in the initial geothermal analysis (IPL, 1980) differed slightly from that taken in the later more detailed geothermal analyses filed with the NEB (IPL, 1982a and 1982f). In the earlier report, an examination of ambient ground temperatures at a depth of 0.5 m was undertaken in order to determine possible pipe temperatures throughout the year in various segments of the route. In the later report one dimensional simulations were used to determine possible worst case scenario ground temperatures at a depth of 1 m (i.e. coldest for frost heave and warmest for thaw settlement); these ground temperatures were used to represent the pipe temperatures in subsequent two dimensional geothermal analyses.

The observed pipe temperatures at the northern permafrost fences fall within these two extremes used for geothermal analyses, hence within the range of pipe temperatures used in the design calculations. Mean annual pipe temperatures following two years of operation ranged from -0.3° to 1°C in this northern section.

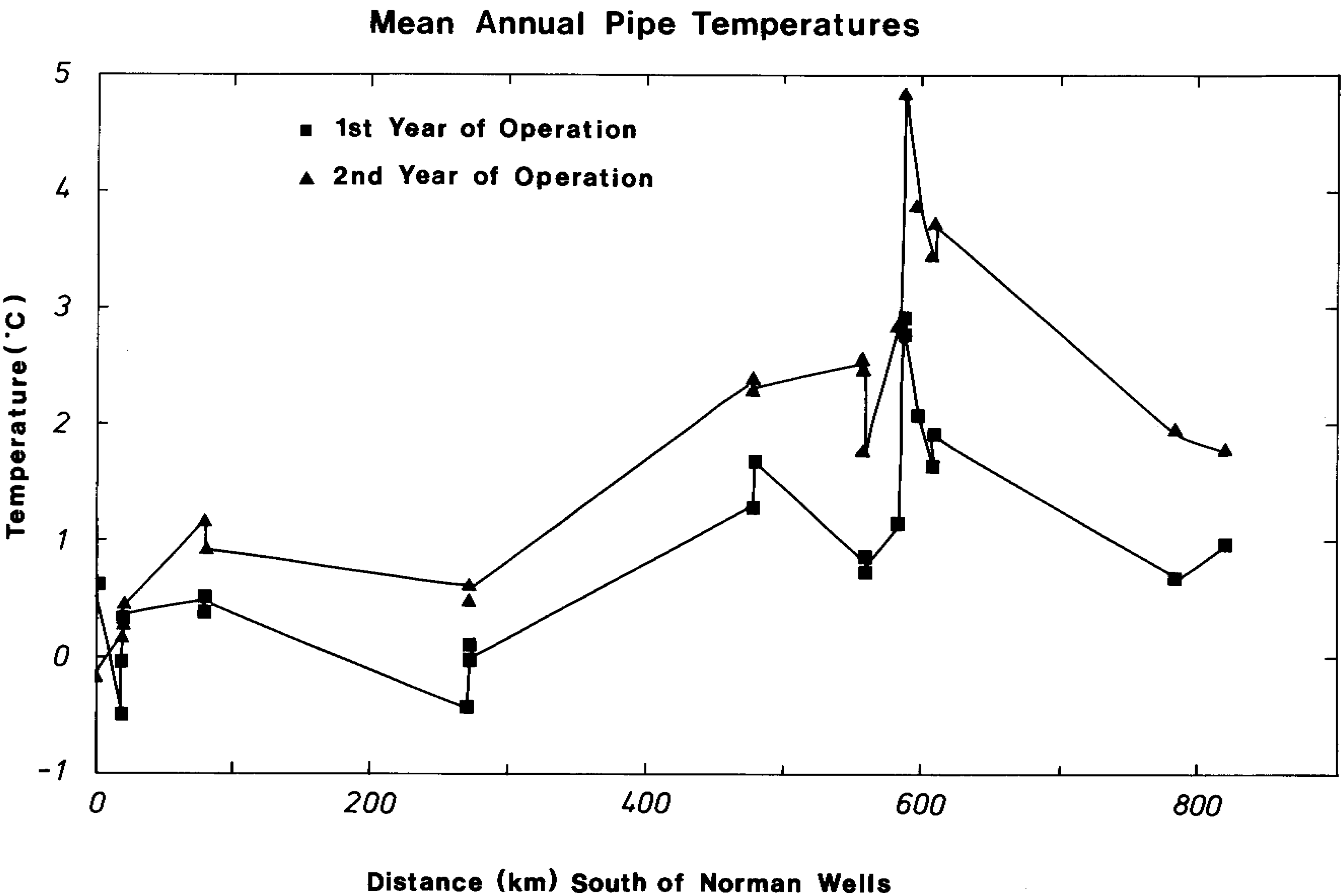


Figure 4-8. Mean annual pipe temperature versus kilometrepost, first and second year of operation.

(Note: The Table Mountain monitoring fences, 85-7A/B/C, km 271-272, were grouped with the northern fences and compared to predicted pipe temperatures for IPL's region 14. The Table Mountain site actually fall within IPL's "region 15" (km 110-376). The pipe temperatures determined for the thaw settlement design analysis in region 15 differ from those of region 14 in that they are warmer. Needless to say that if the observed pipe temperatures at Table Mountain fall below those predicted for region 14, they automatically are also below those of region 15.)

Two slightly different predicted pipe temperature curves are shown for the southern portion of the route in Figure 4-5. Both represent the warmest pipe temperatures expected in IPL's region 16 (km 376-866) and were used in numerical models to determine maximum thaw depths for thaw settlement design; frost heave was not a concern in the south. The first and earliest curve (IPL, 1980) has a mean annual pipe temperature of +5°C. The second or revised prediction (IPL, 1982f), has a mean annual pipe temperature of +6.5°C. Mean annual pipe temperatures are well above 0°C at all fences in this southern section, and ranged from 2° to 5°C after two years of operation. As expected frost heave does not appear to be a concern over this portion of the route.

The observed pipe temperatures in the south have, during the first two years, remained below the design maximum in the summer months; however in the winter months some observations are warmer than predictions. A closer scrutiny of the individual data at each thermal fence reveals that in fact these warmer winter temperatures are recorded at the thermal fences within 25 km downstream from Pump Station 3. Elsewhere observed temperatures fall below the predictions.

4.2 PIPE - GROUND TEMPERATURE COMPARISONS (1984-1987)

4.2.1 Temperature versus time

In order to compare the pipe thermal regime to the ambient ground thermal regime, ground temperatures from a similar depth on the ROW have been selected. The temperature cable located in the deep borehole on the ROW several (4 to 9) metres away from the pipe was selected for the determination of ambient ground temperatures, as any trenching effects or any pipe thermal effects may have already been felt at the shallow cables located generally within a few metres of the trench. The first sensor on this cable, installed at a depth of 1 m, lies at approximately the same burial depth as the pipeline (average depth of cover over the pipe, excluding roach, is 0.9 m).

Plots of pipe temperature versus time (using mid-pipe sensor #2) and the ground temperature versus time (using the 1 m sensor at the deep ROW cable, generally designated as cable T3), for each thermal fence instrumented with pipe temperature sensors are gathered in Appendix C. For convenience only one of the pipe sensors is shown on these plots, since the pipe temperatures recorded at a site are essentially the same at all 5 sensors, generally within a degree. Temperature measurements are taken on average once a month, but plots are drawn as continuous lines for ease of comparison; where large data gaps exist the line is broken. The pipe sensor and ground temperature sensor are both initially at approximately the same depth; with time however their relative position and absolute depth may change as either the ground, or the trench backfill or the pipe move due to settlement or heave. Some indication of the range of trench subsidence observed at each fence will be discussed later in section 4.4; this subsidence includes settlement of the roach.

An examination of the relation between temperature and time (T vs t plots) reveals, since oil flow, a predominance of fences where the pipe temperatures are warmer year round than the ground temperatures at the 1 m sensor. This phenomena occurs at fences in permafrost (e.g. 12B, 10B, 8C, 8B, 8A, 7C, 7A, 3A, 2A) and non-permafrost sites (12A, 10A). The terrain at the deep ROW cable at these sites, whether unfrozen or underlain by permafrost, is characterized by a peat cover or a thick peat surface layer. Prolonged temperature differences between pipe temperature and ground temperature of up to 4 degrees are not uncommon. Differences in the summer of 1986 are generally greater than in the summer of 1985, for example at sites 8A, 8B and 8C: 5 degrees in 1986 versus 1-2 degrees in 1985.

Pipe temperatures are never consistently (at all times) and markedly cooler than ground temperatures. Seasonal variations occur in silty clay/clay till (eg. on the west facing slope at 84-2C), with pipe temperature warmer in the winter yet cooler in the summer.

4.2.2 Running mean annual temperatures

In addition to this graphical comparison of pipe temperatures and ambient ROW ground temperatures, running mean annual values have also been calculated (using the curve fitting routines and interpolation techniques described earlier in section 4.1.3) in order to more accurately quantify the comparison / differences. These calculations and plots of the results, showing trends in running mean annuals of both pipe and ROW temperatures, are reported for each thermal fence in Riseborough et al., 1988; examples are shown in Figure 4-9.

The trends in pipe temperature and ROW temperature revealed by these calculations, and the relationship between pipe and ROW

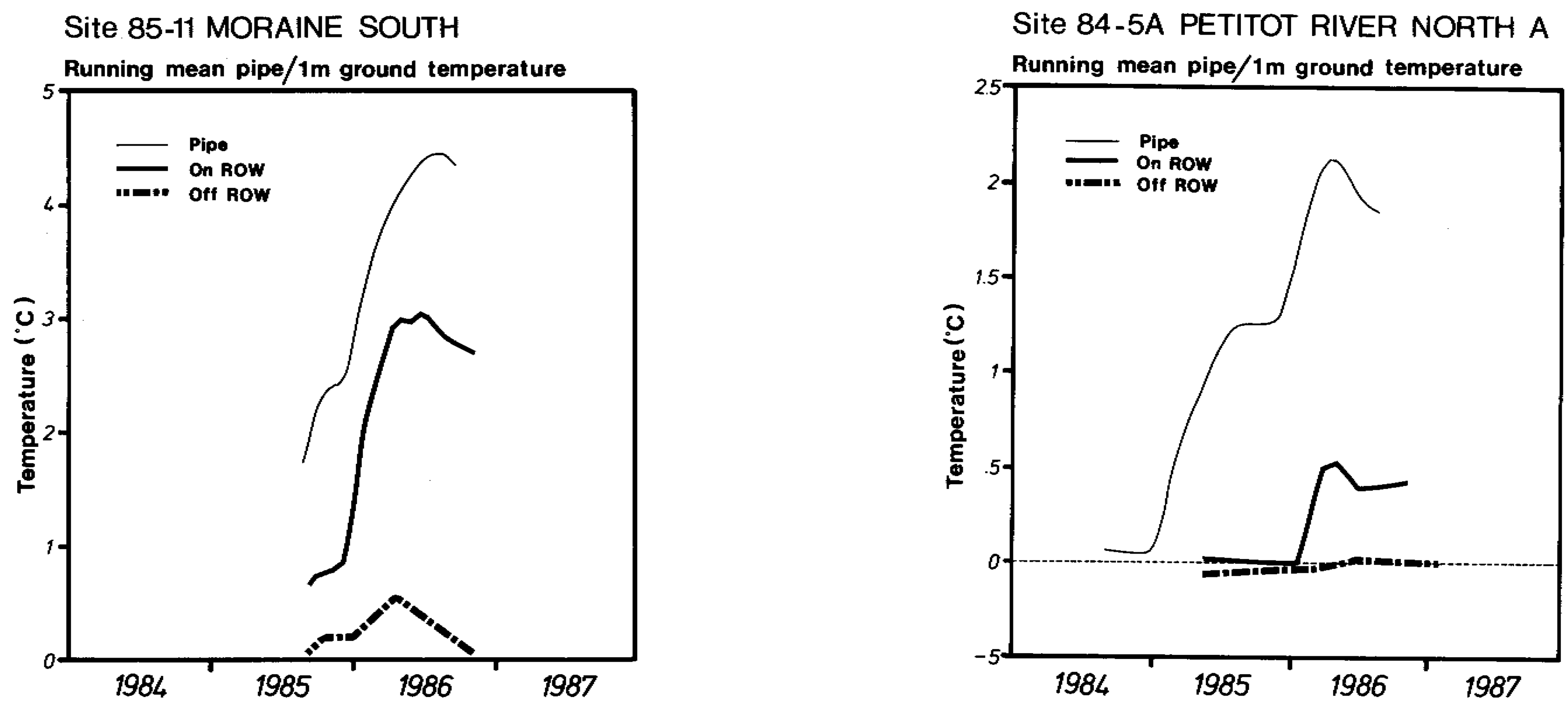


Figure 4-9. Comparison of running mean annual pipe and running mean annual 1 m ground temperature at sites 85-11 (km 597.4) and 84-5A (km 783.0).

temperatures are given for each thermal fence in Table 4-2, for data up to the end of second year of operation. The table indicates qualitatively whether the mean annual temperatures are warming, cooling or variable and whether the rate of change is accelerating, decelerating or stable. Also shown is whether the mean annual pipe temperatures are warmer or cooler than the mean annual ground temperatures. A summary section of the table reveals the general trends of 1) increasing pipe temperatures, but rate of warming decelerating, 2) increasing ROW temperatures, but rate of warming decelerating or variable, and 3) pipe temperatures being warmer than ground temperatures.

The warming noted in mean pipe temperature and ROW temperature was greatest at most fences during the first year of operation, perhaps reflecting the atypical cooling of the trench and ROW due to snow removal during construction and pipeline installation - i.e. before temperature instrumentation and readings. The deceleration in the warming trends may represent the approach to a new, higher, equilibrium surface temperature. Ground temperatures below 1 m on the ROW are generally not in thermal equilibrium with present surface conditions. (This is illustrated for example by the ground temperature envelopes for the T3 cables at site 85-7 in Figure 4-10). Although a new equilibrium surface temperature may have been reached, the thermal response of warm permafrost may nevertheless be slow, particularly for ice-rich soils, due to latent heat effects.

Table 4-3 lists the calculated mean annual temperatures during the first year of pipeline operation and during the second year for the pipe sensors, the ROW (1 m sensor, deep cable). Mean annual ROW temperatures during the second year of operation ranged from -1.8° to +3.8°C, and are on average 1.5 degrees colder than mean annual pipe temperatures.

4.2.3 ROW and off-ROW temperatures

Running mean annual temperatures have also been calculated for the off-ROW temperature cable for a comparison of the running means for the 1 m sensor of the deep ROW and off-ROW cables (generally cables T3 and T4). Results are available in Riseborough et al., 1988. Examples from a few fences are included in Figure 4-9. Table 4-4 summarizes qualitatively the results of these comparisons and the trends revealed in the off-ROW running means, based on data to the end of the second year of operation. Mean annual temperatures on the ROW are in general warmer than those off-ROW.

The off-ROW temperatures, unlike the pipe and ROW, were not changing at a majority of the thermal fences; 25% of fences showed off-ROW warming, compared to 65% showing on-ROW warming and 75%

Table 4-2. Trends in pipe and ground temperatures.

Monitoring sites (arranged north to south)

Site	1	2	2	2	3	3	7	7	7	4	4	8	8	8	9	10	10	11	12	12	5	5	6
Fence		A	B	C	A	B	A	B	C	A	B	A	B	C		A	B		A	B	A	B	
<u>Temperature Trend:</u>																							
Pipe:	C	V	V	V	W	W	W	V	W	W	V	W	W	W	W	W	W	W	W	W	W	W	W
Trend is:	D			D	*		D	D	D	D	*	D	D	D	D	D	D	D	D	D	D	D	D
R.O.W.:	V	V	W	W	W	W	W	V	V	W	V	W	*	*	W	W	V	W	W	W	W	W	W
Trend is:			D	V	A	D	V			V		D			D	D		D	D	A	A	*	D
<u>Temperature Relationship:</u>																							
PIPE : ROW	W	V	W	C	W		W	W	W		C	W	W	W	W	W	W	W	W	W	W	W	W

CODES W = Warmer or Warming
C = Colder or Cooling
V = Variable
* = Stable or Equal
A = Accelerating
D = Decelerating

Totals:	W	C	V	*	A	D
TRENDS:						
Pipe	17	1	5	0	0	18
R.O.W.	15	0	6	2	3	8
RELATIONSHIPS:						
Pipe : R.O.W.	18	2	1	0		

Note: - Based on comparisons of running means calculated up to the end of the second year of operation.
- Ground temperatures are from the sensor at a nominal depth of 1 m on the deep cables.

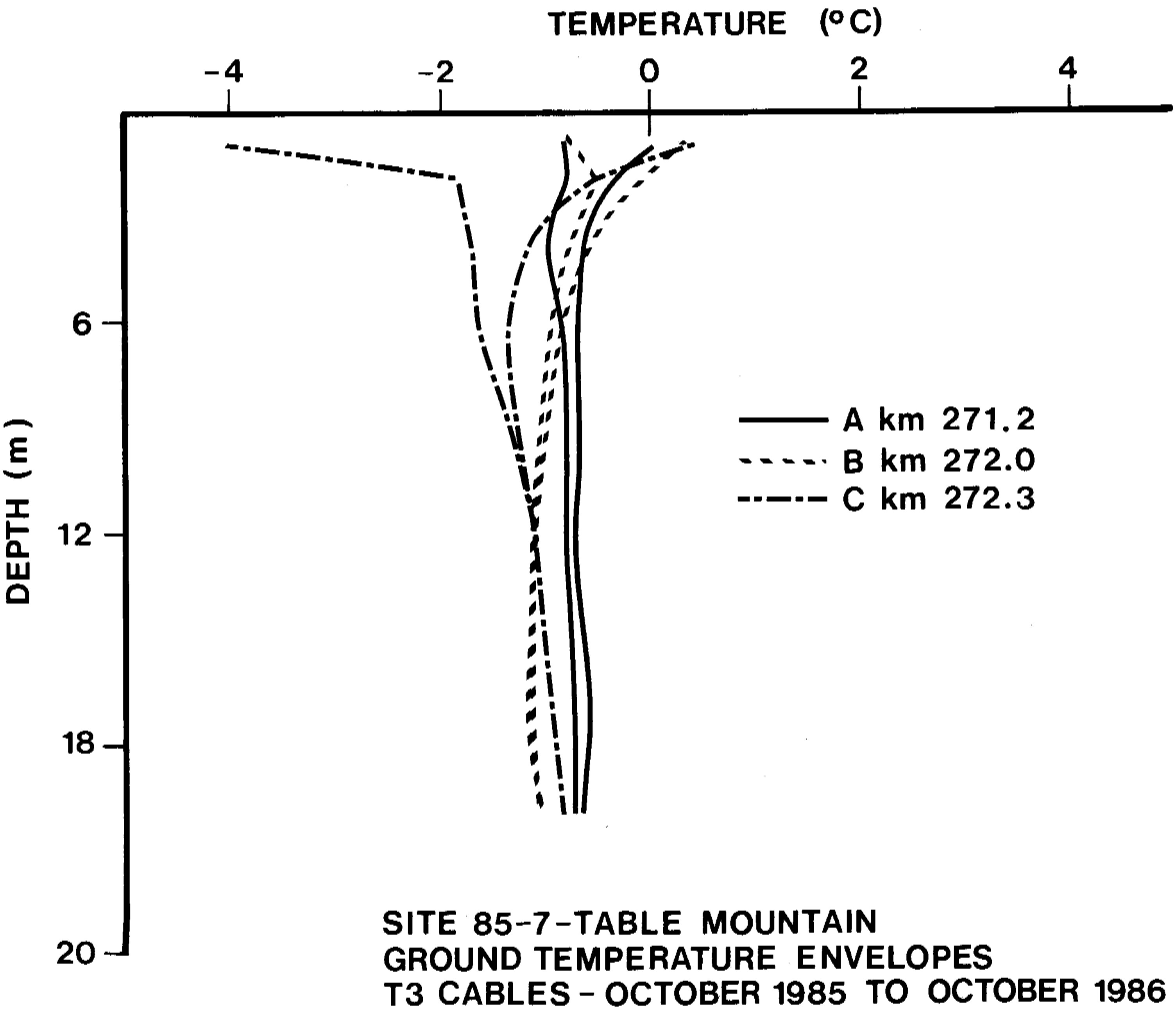


Figure 4-10. Ground temperature envelopes (October 1985 to October 1986) for the deep ROW cable at three thermal fences at Table Mountain site 85-7.

Table 4-3. Mean annual temperatures.

SITE	km	PIPE TEMPERATURES YEAR 1	PIPE TEMPERATURES YEAR 2	GROUND TEMPERATURES AT 1m DEPTH ON ROW YEAR 1	GROUND TEMPERATURES AT 1m DEPTH ON ROW YEAR 2	GROUND TEMPERATURES AT 1m DEPTH OFF ROW YEAR 1	GROUND TEMPERATURES AT 1m DEPTH OFF ROW YEAR 2
84-1	0.02	0.62	-.16	-.84*	-.86*	-1.85	-2.25
84-2A	19.0	-.52	0.18	-.44	0.06	-.45	-1.05
84-2B	19.3	-.04	0.29	-.26	-.23	-2.29	-2.46
84-2C	19.6	0.37	0.44	1.24	1.26	-.85	-1.03
84-3A	79.2	0.48	1.18	-1.57	-1.15	-1.92	-2.80
84-3B	79.4	0.42	0.93	0.38	0.50	-2.26	-2.33
85-7A	271.2	-.44	0.60	-.26**	-.01	-.66	-1.01*
85-7B	272.0	0.12	0.44	-.64**	-.85	-.61**	-1.37*
85-7C	272.3	0.00	0.57	-1.14	-1.59	-.98**	-1.05*
84-4A	478.0	1.28	2.41	-	2.55	0.65	1.56
84-4B	478.1	1.69	2.33	2.49	2.91	0.39	0.86
85-8A	557.8	0.84	2.56	-.55	-.25	-.80	-.72
85-8B	558.2	0.90	2.50	-.48	-.50	-.96	-1.05
85-8C	558.3	0.73	1.76	-.23	-.36	-.24	-.25
85-9	583.3	1.14	2.86	2.09	3.60	1.08	2.49
85-10A	588.3	2.91	4.84	-.06	2.38	0.67	1.49
85-10B	588.7	2.71	4.84	0.99	1.23	-.44	-.59
85-11	597.4	2.07	3.90	0.76	2.76	0.20	0.14
85-12A	608.6	1.62	3.45	-.49	1.67	-.25	0.25
85-12B	608.7	1.91	3.71	-.92	-.79	-.90	-1.12
84-5A	783.0	0.68	1.93	-.01	0.41	-.04	-.01
84-5B	783.3	0.65	1.94	-.06	-.10	-.04	-.14
84-6	819.5	0.97	1.78	-.18	-.16	-.03	-.02

NOTES:

* average of 2 cables; elsewhere 1 cable.
** a full year's data is not available, therefore mean based on less than 12 months.

1. Temperature cable on-ROW is deep cable (generally T3) located furthest from the pipe.

2. Mean annual temperatures were calculated by;
   i) performing curve fitting to the approximate monthly readings, using a cubic spline interpolation
   ii) interpolating weekly values
   iii) YEAR 1 - taking values for 52 week period from April 1985 to March 1986 and averaging.
   iv) YEAR 2 - as above but for the 52 week period from April 1986 to March 1987

3. 1 m sensor is nominally at a depth of 1 m.

Table 4-4. Relationships between running mean temperatures on and off the Right-Of-Way (R.O.W.) at 1 m depth.

	Monitoring sites (arranged north to south)																						
Site	1	2	2	2	3	3	7	7	7	4	4	8	8	8	9	10	10	11	12	12	5	5	6
Fence		A	B	C	A	B	A	B	C	A	B	A	B	C		A	B		A	B	A	B	
<u>Temperature Trend:</u>																							
on R.O.W.	V	V	W	W	W	W	W	V	V	W	V	W	*	*	W	W	V	W	W	W	W	W	W
Trend is:			D	V	A	D	V			V		D			D	D		D	D	A	A	*	D
off R.O.W.	C	V	C	V	W	*	V	V	V	W	V	*	*	*	W	W	C	V	W	V	*	W	*
Trend is:	A		*		A					D					D	D	*		*			D	
<u>Temperature Relationship:</u>																							
on : off R.O.W.	W	*	W	W	W	W	C	V	C	W	W	W	W	W	W	W	W	W	W	W	W	W	C

CODES W = Warmer or Warming
C = Colder or Cooling
V = Variable
* = Stable or Equal
A = Accelerating
D = Decelerating

	Totals: W	C	V	*	A	D
TRENDS:						
on R.O. W.	15	0	6	2	3	8
off R.O. W.	6	3	8	6	2	4
RELATIONSHIPS:						
on : off	18	3	1	1		

Note:
- Based on comparisons of running means calculated with data through the end of March 1987.
- Ground temperatures are from the sensor at a nominal depth of1 m on the deep cables.

showing pipe temperature warming. The off-ROW trends were more variable, both in terms of rate of change and type of change.

These off-ROW observations indicate that the ground thermal response to the recent approximately 2 degrees warming in mean annual air temperature recorded at both Norman Wells and Fort Simpson AES stations (see discussion in Chapter 3) has not been uniformly one of warming. The general warming observed on the ROW is thus more likely a result of clearance and pipeline construction rather than a response to increasing air temperature.

Table 4-3 also lists the mean annual temperature calculated for the off-ROW 1 m sensor at each fence for the first year and second year of pipeline operation. The off-ROW mean temperatures are on average colder than the ROW mean temperatures by 1 degree; during the second year of operation these off-ROW temperatures ranged from -2.6 to +2.6°C, or 2.5 degrees below pipe temperatures.

4.2.4 **Observations and predictions-the behaviour of an ambient line**

The comparison of running mean pipe temperatures to running mean ROW ground temperatures (1 m sensor, deep cable) revealed that mean annual pipe temperatures are generally warmer, on average by 1.5 degrees (difference ranges from about 1.5° colder to 5° warmer). This relationship occurs at a predominance of fences, both in permafrost and unfrozen terrain. This temperature difference probably reflects the more disturbed terrain conditions in the trench as compared to the rest of the ROW. The trench may be filled with local or select backfill, depending on the site. Post construction changes initially resulted in ditchline depression along a third of the pipeline (based on interpretation of July 1986 air photos (Hardy, 1986). The subsided ditch is also often filled with ponded, or occasionally flowing, water (Wishart and Fooks, 1986). About 80 km of trench with subsidence >20 cm were backfilled during winter remedial programs in 1986 and 1987, involving >100 000 m^3 of material.

The thermal conditions of the disturbed trench are thus generally different to those of the cleared ROW. In that the pipe thermal regime follows a seasonal cycle, the temperature of the pipeline does, on average, appear to be controlled by the adjacent (i.e. trench) ground temperature. However the thermal conditions of the trench are in general warmer than those of the remainder of the ROW. Further instrumentation to better define the thermal regime of the trench has been undertaken both by IPL and government.

The thermal influence of the generally wet trench may also help to explain the warmer winter pipe temperatures observed since start-up. Heat required to freezeback the wet trench would delay, prevent or reduce winter cooling. TDR measurements confirm that ground conditions in the vicinity of the trench are unfrozen during the winter months at many monitoring sites (see section 4.3.1).

The pipe temperature increase recorded in the southern portion of the route on passing through Pump Station 3 indicates the pumping process influences the pipe thermal regime. Observations from the thermal fences near Pump Station 3 suggest that this increase in pipe temperature due to pumping requires more than 20 km of pipeline to decay.

4.3 ACTIVE LAYERS AND THAW DEPTHS (1984-1987)

4.3.1 Observations

Information on the thickness of the active layer has been derived from the temperature cables located at the monitoring sites. The active layer is thermally defined by the maximum penetration depth of the 0°C isotherm for a given thaw season. The cross-section of contoured ground temperatures at site 84-1 (Figure 4-11) illustrates the changes in the position of the 0°C isotherm (i.e. active layer) from September 1984 to September 1986. The resolution of the position of the active layer is constrained by the 50 cm sensor spacing on the shallow temperature cables and by the 1 m spacing on the deep cables. Hence the active layer is described as being for example > or < some value. The interpolated position of the isotherm is then corrected for any surface subsidence to yield active layer thickness. At sites with fine-grained soils, the actual thickness of thawed/unfrozen material is often greater than that determined by the 0°C isotherm position, due to the freezing point depression of the soils (see for example Williams, 1982, Chapter 7 for a discussion of soil-water relationships).

Active layer thickness, determined from the ground temperature cable measurements on the ROW at the end of 1987 thaw season, at fences 84-2A and 2C located on the previously cleared CNT alignment varied from 2 to >2.5 m on the level terrain of 2A to >4.5 m on the west-facing slope of 2C. Active layers at fence 2B, also located on the CNT line, but covered with an insulating layer of wood chips, have been confined to <1 m, i.e. within the wood chip layer.

Elsewhere, at sites newly cleared or recently cleared (e.g. helipads a few years prior to construction), the ROW active layer at the end of 1987 ranged from <0.5 to >2.5 m. At sites with thick organic soils (>1.2 m), all newly cleared, active layers ranged from <0.5 to >2 m. Active layers off-ROW at the end of the 1987 thaw season were generally less than those on ROW and ranged from <0.5 to >1.0 m.

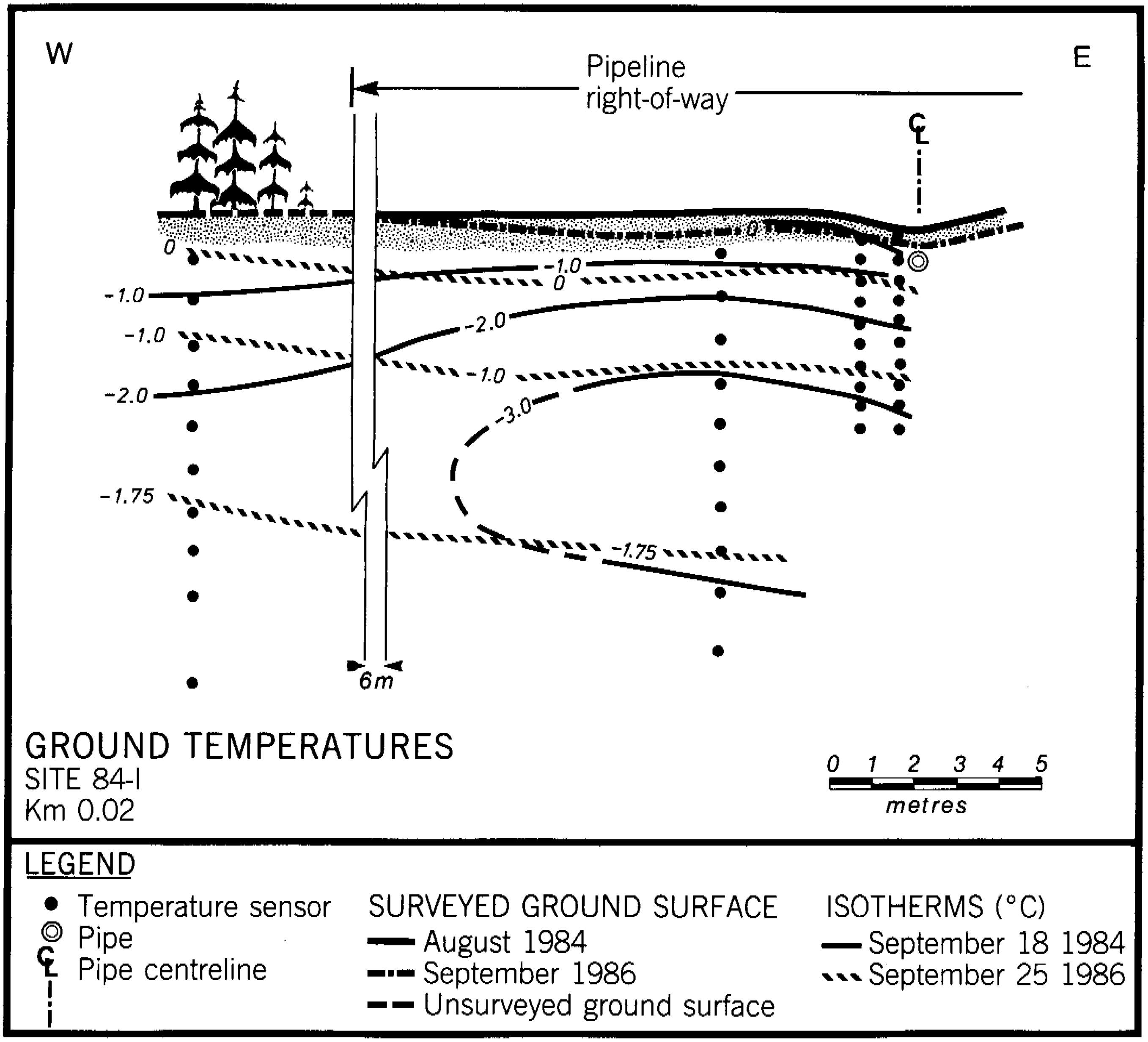


Figure 4-11. Site 84-1: Ground temperature isotherms, September 1984 and to September 1986. The 0°C isotherm represents the position of the active layer.

The 0°C isotherm on-ROW has deepened by up to >1 m from 1984 to 1987 in response to clearing and construction activities; by comparison off-ROW active layers have changed very little over this period. Warm thin (1-2 m) permafrost has disappeared beneath the ROW at two southern fences (85-9 and 85-11), both underlain by ice-poor coarse grained soils. The ground thermal response in ice-rich terrain and in thick ice-rich peat sites has generally been slow due to latent heat effects. Although little change in permafrost temperature has occurred at these sites, active layers have deepened.

Transects along the thermal fences probing the depth to the frost table have also been undertaken at the end of the thaw season at most thermal fences, using a 1 or 2 m probing interval. Transects measured at site 84-1 are illustrated in Figure 4-12. The transects provide a more continuous profile of the thaw depths across the ROW and the pipe trench. These transects are not strictly a measure of the depth of the 0°C isotherm, but rather of the thickness of unfrozen and unbonded material (which as mentioned earlier may be of greater thickness in fine grained soils with a freezing point depression). Thaw depths at many fences in 1987 exceeded the maximum depth of penetration of the probe (1.75 m), particularly in the vicinity of the trench. These transects have generally shown that the thaw depths are greater than the active layer. The general use of the 0°C isotherm as the thermal boundary delineating the depth of thaw could thus lead to underestimating the thickness of unfrozen ground and hence the amount of thaw settlement during geothermal design.

Thaw depths in the trench adjacent to the pipe are generally greater than elsewhere on the ROW. The occurrence of a perennial thaw bulb around the pipe at several southern sites (as of October 1987, sites 84-5A, 84-5B, 85-10B and 85-12B) has been confirmed by TDR readings. The dielectric constants interpreted from the TDR data (Patterson, 1988) measured to depths of 1.7 m in the trench show no seasonal variation and are indicative of unfrozen soil water.

4.3.2 Comparison of observations to predictions

One of the principal steps in IPL's thaw settlement design process involved the prediction of maximum anticipated thaw depths beneath the pipe. The geothermal analyses used in the pipeline thaw settlement design are outlined in detail in two reports (IPL, 1982a and 1982f) and reviewed in Volume I, Chapter 3, section 3.3. Design thaw depths from the ground surface, based on 30 year simulations, were established for various regions and soil profiles, as follows:

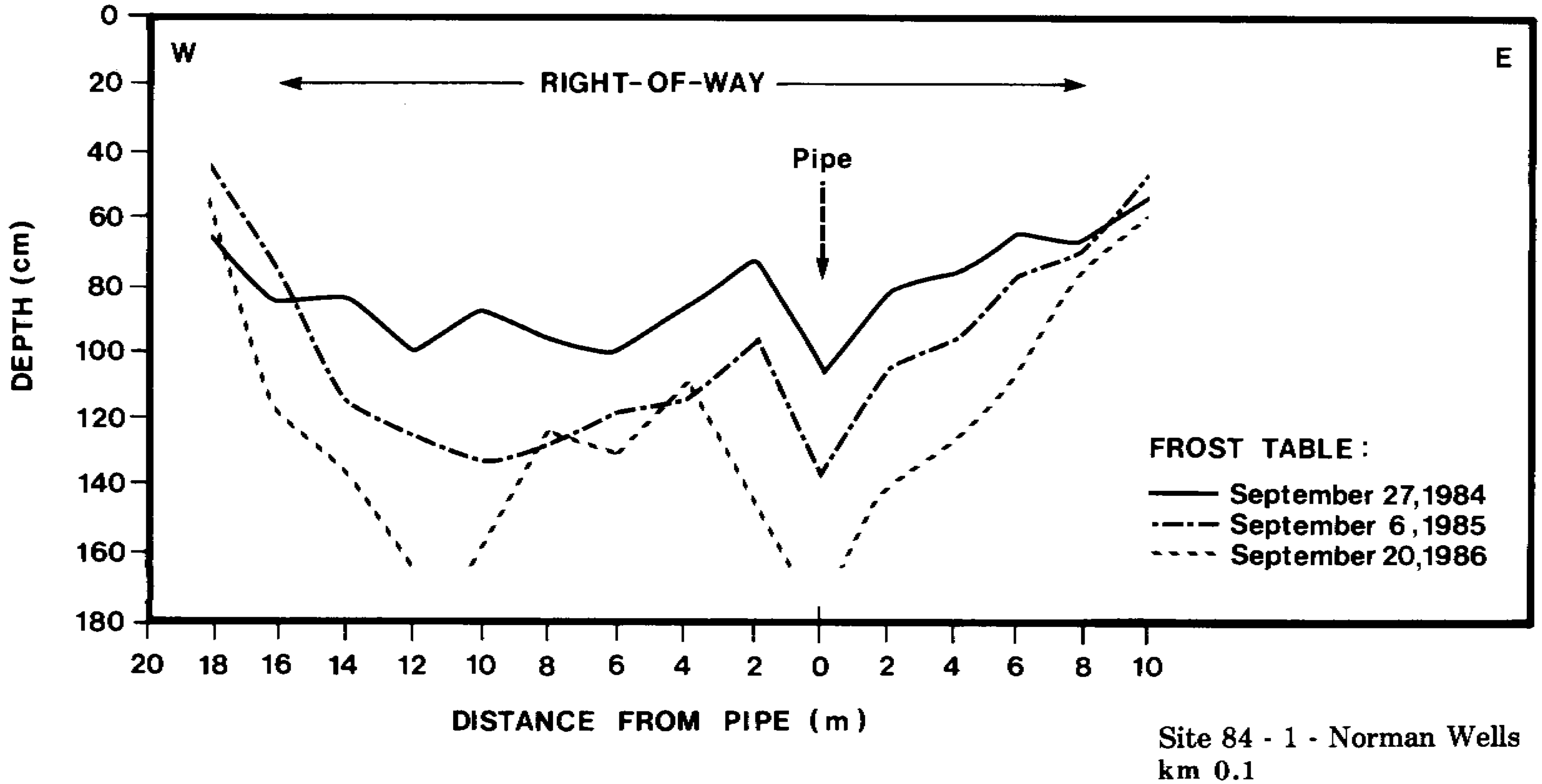


Figure 4-12. Site 84-1, km 0.02: Fall transects probing to the frost table.

1) low moisture content till, km 0 to 100: 9.1 m
2) low moisture content till/clay, km 100 to 400: 12.2 m
3) organic veneer (1.2 m) km 400 to 868: 9.1 m
4) thick organics (>1.2 m), km 400 to 868: 6.1 m.

Plots of the evolution of thaw depth below the pipe centerline as a function of time, as modelled by the above geothermal simulations, are given in Hardy (1982f). These 30 year simulations assume that heat transfer is purely conductive and that both clearance and pipeline start-up occur simultaneously. The simulations for mineral soil (1 and 2, above) included a 30 cm surface organic layer. Since greater ground thermal disturbance is expected to result from construction and clearing activities, the predictions for the time since site establishment (i.e. since pipe laying) were therefore selected for comparison to observations. This comparison it should be noted involves generic worst case predictions; individual simulations replicating the soil profile and thermal conditions of each fence were not performed. The predicted thaw depths are relative to the original ground surface position and therefore probably do not take any thaw settlement into account. The geothermal simulations of level terrain involved a right-of-way width of 30 m. The width of the ROW at all thermal fences, with the exception of 84-3A, was less than 30 m (see Table 2-5 for exact dimensions at each fence).

To compare design and observation, short term thaw depths were derived from the above mentioned plots of the evolution of thaw depth as a function of time beneath the pipe. Thaw depth at two times were extracted: i) 2.5 years, time since the establishment of the 1985 sites to the end of the 1987 thaw season, and ii) 3.5 years, time since the establishment of the 1984 sites to the end of the 1987 thaw season. Approximate thaw depths for each of these cases for each of the four simulation runs are as follows:

Run 1 -	2.5 years: 2.5 m	
	3.5 years: 3 m	fences 1, 3A & 3B
Run 2 -	2.5 years: 4 m	fences 7A, 7B & 7C
	3.5 years: 4.5 m	
Run 3 -	2.5 years: 2.5 m	fences 8A, 8C & 11
	3.5 years: 3 m	
Run 4 -	2.5 years: 1.9 m	fences 8B, 10B & 12B
	3.5 years: 2.1 m	fences 5A, 5B & 6

The table above also indicates how thermal fences have been paired with these predictions for comparison.

The above predictions for thaw depths may not necessarily be predictions of the depth of the 0°C isotherm. Although it was not specified, the geothermal simulations may have used a lower temperature for the freezing point and selected the depth of that isotherm as the thaw depth. The comparison performed here involves the use of the observed 0°C isotherm depth, determined from the temperature cables (none of which lie directly beneath the pipe) and the use of thaw depth predictions beneath the pipe.

All permafrost fences except those in the previously cleared 1960's CNT alignment, i.e. site 84-2, are included. Observations to the end 1987 at the northernmost fences (1, 3 & 7) are less than the worst case predictions. Borehole lithology logs from site 84-1 and site 85-7 indicate that at these sites the surface organic layer remaining after construction, though not uniform in thickness, was often less than the 30 cm used in the geothermal simulations.

Observations at the remaining fences were also equal to or less than predictions, with a few exceptions: i) 10B and 11, where the thin permafrost has disappeared, and ii) 8A and 5A where some observations exceeded predictions.

4.4 SURFACE CHANGE AND THAW SETTLEMENT (1984-1987)

4.4.1 Observations

The following discussion is based solely on data collected at the instrumented monitoring sites. The topography surveys conducted at the thermal fences record overall vertical movements in the ground surface to an accuracy of 10 cm over an approximately 20 m x 20 m grid, using a 1 or 2 m station spacing. Surface settlement calculated from these elevation changes represent minimum settlement on the ROW, since in all cases the baseline survey was taken one or two thaw seasons following ROW clearance. Examples of surface settlement contours derived from these surveys are given in Figure 4-13 for site 84-1 and site 85-7B.

Variable amounts of surface settlement have occurred on the right-of-way since clearing and pipeline construction. Outside the trench this settlement is due primarily to thaw subsidence of ice-bearing sediments, although shrinkage and deflation of organic material since construction may also be a contributory factor in areas of thick organic terrain. It should be emphasised that settlement data presented relates to movement of the ground surface, rather than the pipe itself.

Table 4-5 summarizes the range of settlement observed at each surveyed site through to the end of the 1987 thaw season. The observation period is specified for each thermal fence since only those sites considered to have potential for continued thaw settlement were resurveyed in 1987. The table divides the data at each fence into two areas, the vicinity of the trench (2 m on either side of the pipe) and the remainder of the ROW, and for each area indicates the range of recorded settlement.

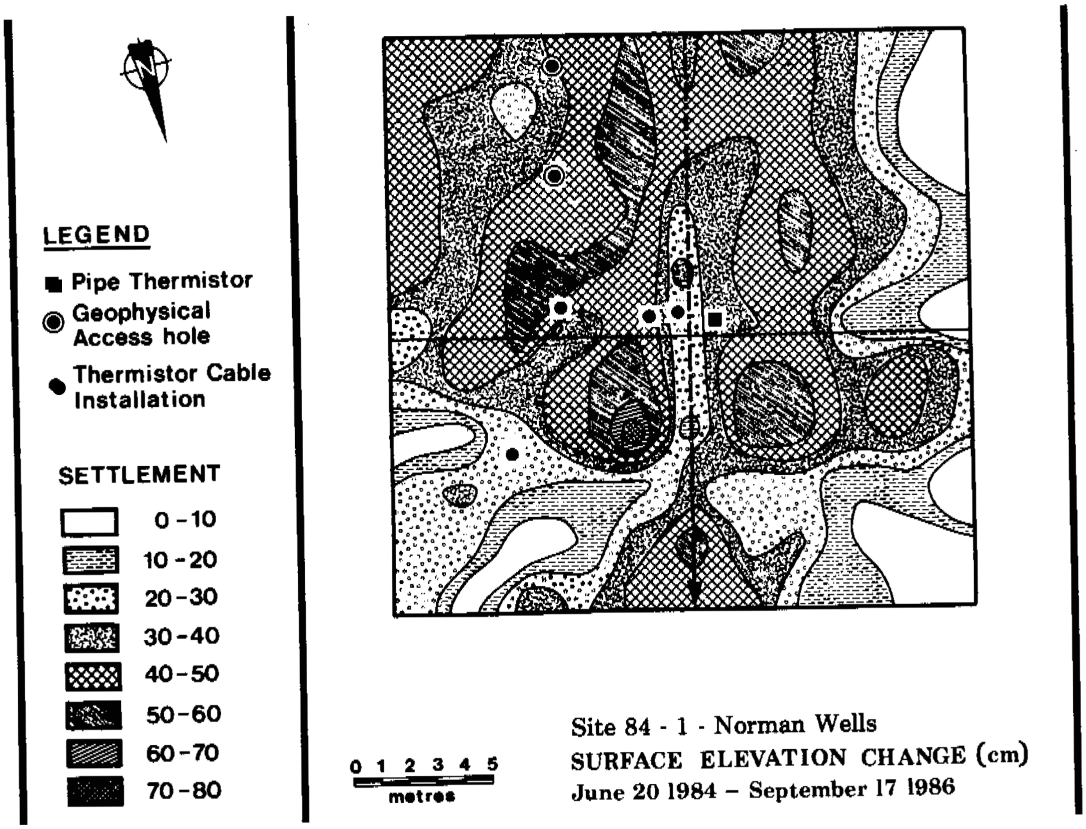


Figure 4-13a. Site 84-1, km 0.02: Contoured ground surface settlement, June 1984 to September 1986.

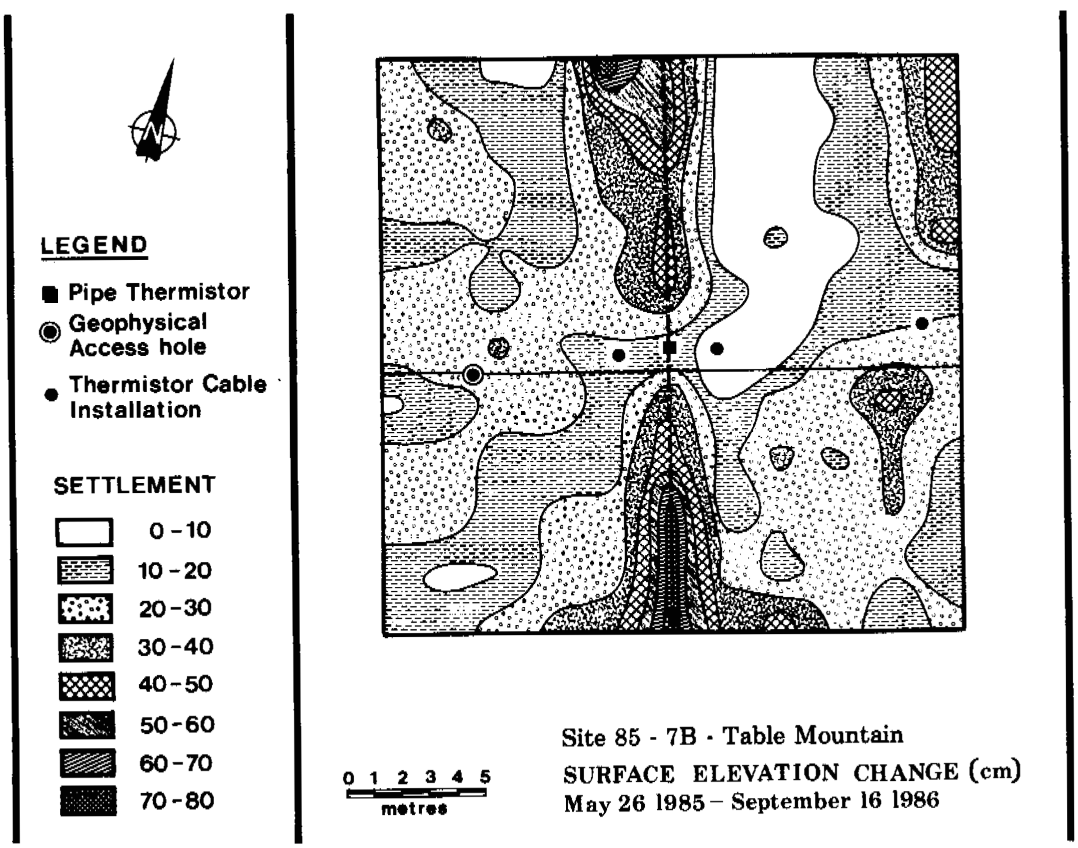


Figure 4-13b. Fence 85-7B, km 272.0: Contoured ground surface settlement, May 1985 to September 1986.

TABLE 4-5. Surface settlement recorded at study sites.

Fence	Observation Period	Range of Settlement * (cm) Trench Area	ROW
84-1	20/6/84 - 29/8/87	>10 - <70	0 - 70
84-2A	21/8/84 - 17/9/86	10 - 30	0 - 20
84-2B	22/8/84 - 28/8/87	0 - <40	0 - <60
84-2C	22/8/84 - 17/9/86	0 - 20	0 - 30
84-3A	22/8/84 - 22/8/87	>0 - <60	>0 - <60
84-3B	22/8/84 - 22/8/87	0 - <20	0 - <40
85-7A	26/5/85 - 27/8/87	10 - <90	0 - 40
85-7B	26/5/85 - 27/8/87	0 - 80	0 - <60
85-7C	26/5/85 - 27/8/87	>10 - <70	>0 - <40
84-4A	24/8/84 - 15/9/86	0 - 50	0 - 20
84-4B	24/8/84 - 15/9/86	0 - 30	0 - 30
85-8A	25/5/85 - 26/8/87	0 - <50	0 - <30
85-8B	25/5/85 - 28/8/87	0 - <90	0 - <90
85-8C	25/5/85 - 28/8/87	0 - <120	0 - <100
85-9	24/5/85 - 13/9/86	0 - 20	0 - 10
85-10A	23/5/85 - 28/8/87	0 - <40	0 - <40
85-10B	23/5/85 - 28/8/87	>10 - <130	0 - 40
85-11	23/5/85 - 14/9/86	backfilled winter/86	0 - 20
85-12A	22/5/85 - 25/8/87	0 - <100	0 - <50
85-12B	22/5/85 - 25/8/87	0 - <150	0 - <50
84-5A	26/8/84 - 19/8/87	0 - <60	0 - <30
84-5B	25/8/84 - 19/8/87	0 - <50	0 - <20
84-6	25/8/84 - 19/8/87	0 - <60	0 - <30

* The range of settlement (cm) determined from the surface elevation surveys is defined by the minimum and maximum amount observed for each of two areas:

1) Trench Area: includes trench and 2 m on either side of the pipe centreline
2) ROW Area: the remainder of the surveyed ROW

In the trench area the maximum recorded settlement has reached 50 cm or more at 13 of the 23 thermal fences, with 3 fences showing a maximum of 100 cm or more. Some of this settlement was initially probably a result of the subsidence of the trench backfill which was placed as a frozen and uncompacted berm over the pipe during winter construction. During the winter of 1986, remedial backfill was placed in the trench at two fences, 85-11 and 85-8C; this new backfill has continued to subside at the latter site.

For the ROW area outside the trench, maximum recorded settlements of 50 cm or more have been observed at 6 permafrost fences. A few sites, notably 84-1 (km 0.02) and 84-3A (km 79.2), where the originally hummocky terrain was levelled on the ROW and much of the surface organic layer removed during construction, have again developed a conspicuous hummocky relief (over 50 cm, e.g. site 84-3A Figure 4-14). Much of this hummocky relief at 84-3A developed during the 1984 thaw season prior to the first survey, due to the melting of near-surface ice (up to 80% ice by volume observed in top 1-2 m of boreholes and trench sections).

Right-of-way surface settlement is continuing, both in the trench and on the remainder of the ROW, and the rate of settlement has been variable from year to year and site to site. Figure 4-15 shows surface change at three sites, recorded in terms of (a) cumulative settlement by percent area from the first survey date to August 1987, and (b) the range of settlement measured between successive surveys. The diagrams are also divided to show the contrast between the trench area and the remainder of the right-of-way. The differential settlement plots show that surface settlement is ongoing but at a variable rate. The continuation of settlement in the trench in subsequent years however is likely due to settlement of newly thawed ground beneath the depth of pipe burial.

At site 84-1 cumulative settlement of 40 to 60 cm has occurred across much of the right-of-way since June 1984. Settlement is continuing, but at a reduced rate compared to the first year of observation. At site 84-3A, cumulative settlement of 20 to 40 cm has occurred since the August 1984 survey. Although settlement is continuing to occur, comparison of data from successive surveys suggest that the rate of surface movement is decreasing. At site 85-8C, cumulative settlement of up to 120 cm in the trench area and 100 cm on the right-of-way has been recorded since May 1985. Across most of the ROW cumulative settlement is <40 cm. This site shows an irregular rate of settlement, probably reflecting variations in the thickness of the insulating peat surface layer and in the ice content of underlying sediments.

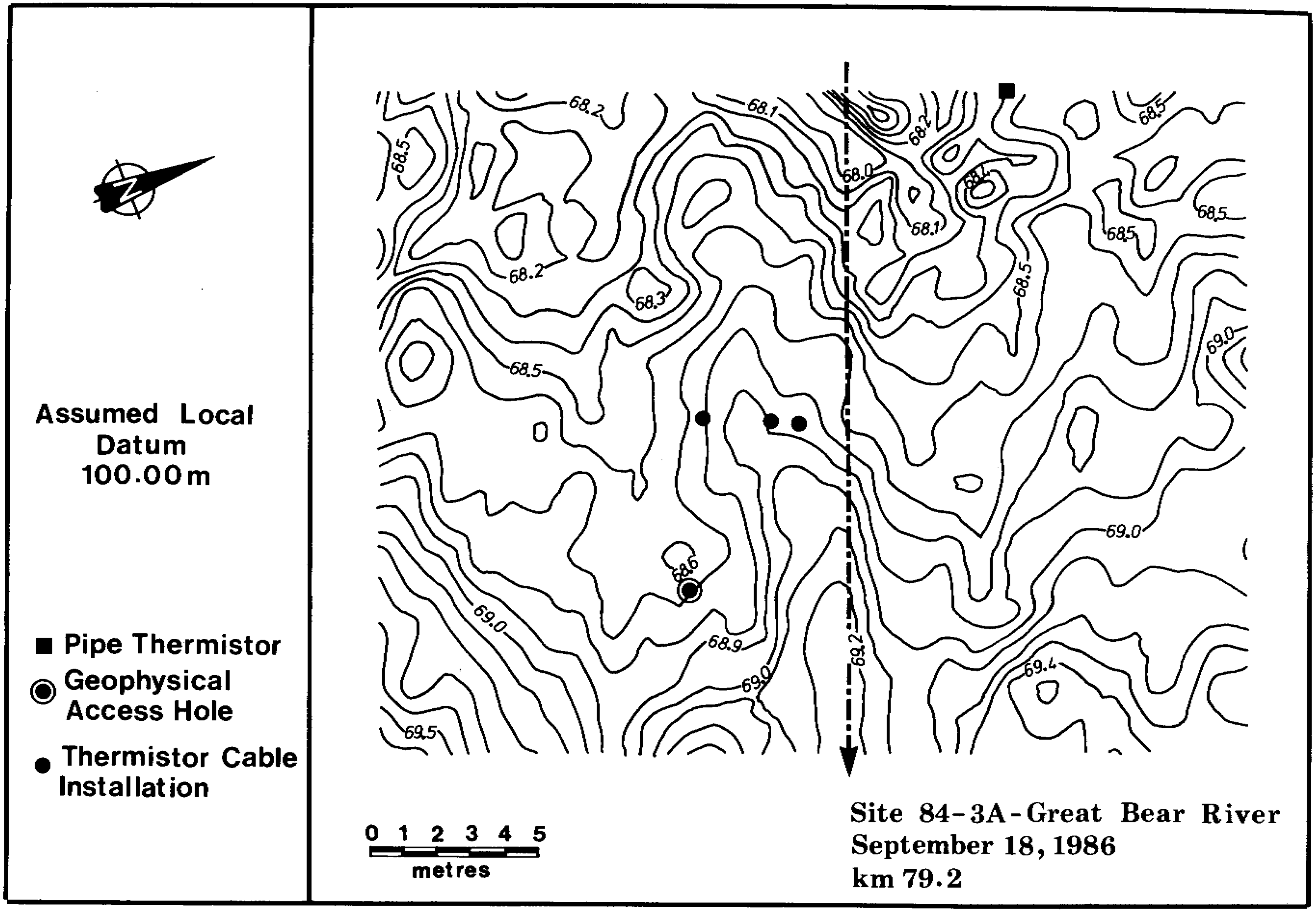


Figure 4-14. Fence 84-3A, km 79.2: Surface elevation contour map, September 1986.

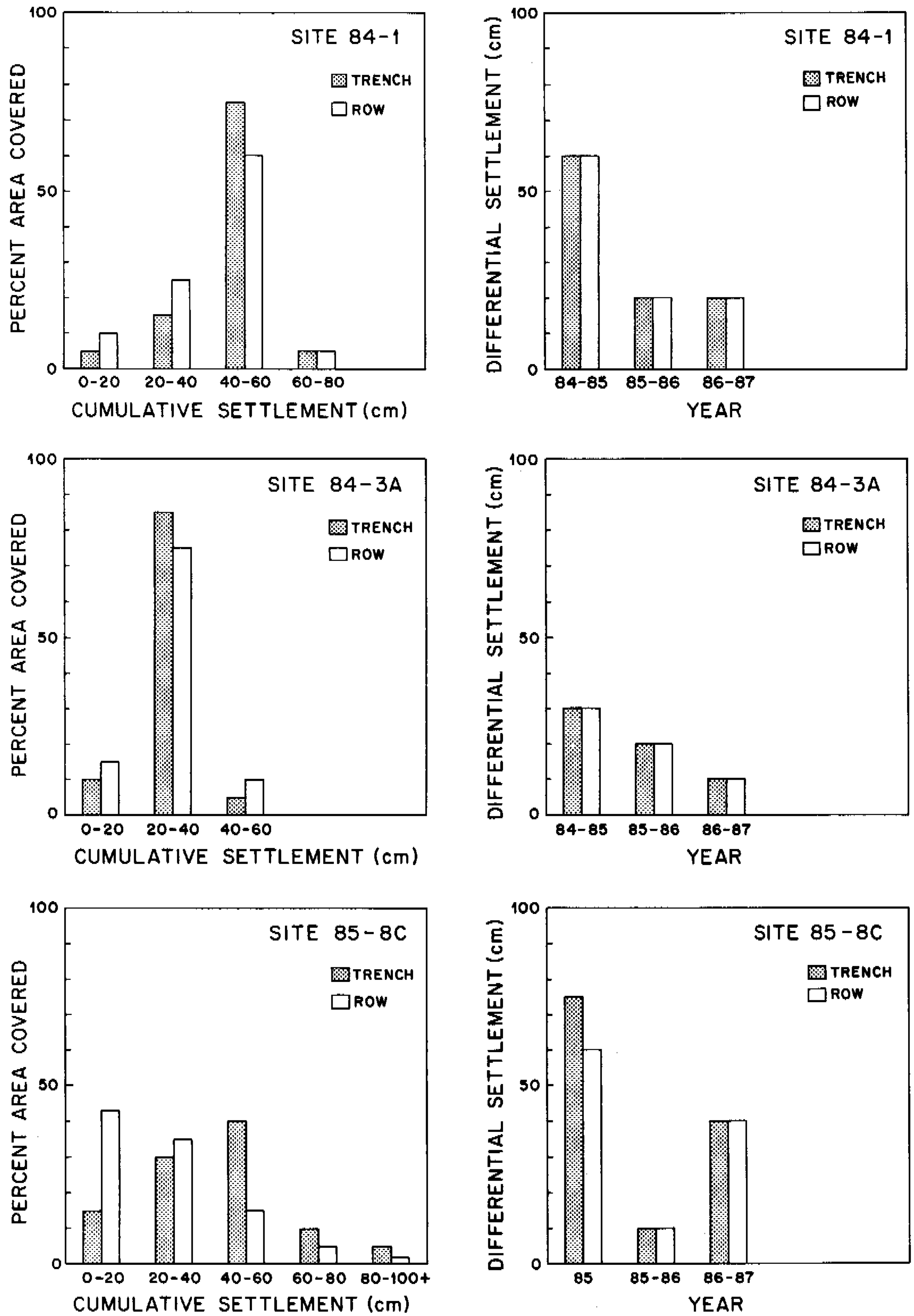


Figure 4-15. Surface settlement at sites 84-1, 84-3A and 85-8C recorded in terms of cumulative settlement by percent area to August 1987 (left), and range of settlement measured between successive surveys (right).

4.4.2 Comparison of observations to predictions

Design thaw depths

Thaw settlement design and predictions were reviewed in Volume I, Chapter 3, section 3.3. These predictions followed lengthy field work (terrain typing and borehole drilling), laboratory work (soil physical and thaw settlement properties tests), and numerical analyses to calculate design thaw depths for various construction segments and terrain types. The design thaw depths in turn were used to calculate thaw settlement beneath the pipe.

Individual thaw settlement predictions were made for most boreholes in the soil data bank, using the appropriate design thaw depth for the terrain type and borehole location. The settlements were determined by dividing the borehole into soil layers and summing up the calculated settlement for each layer beneath the pipe. Each soil layer was identified within one of 6 major soil groups and assigned a water content. The thaw strain and coefficient of compressibility of the layer were then derived from correlations established for each soil group during laboratory thaw settlement tests.

Borehole settlements were sorted by terrain type and construction spread. Statistics (mean settlement and standard deviation) based on all data for a given design thaw depth for each terrain type were also derived. Thaw settlement design values were established from these analyses for various segments of the route as follows (IPL, 1982f), these values represent settlements beneath the pipe:

1) km 0 to 78 , all terrain types except thick peat: 0.80 m
2) km 78 to 440, all terrain types except thick peat: 0.75 m
3) km 440 to 868, all terrain types except thick peat: 0.70 m
4) km 0 to 868, thick peat (>1.2. m): 1.00 m

Thaw settlement calculations for time periods less than 30 years, i.e. for thaw depths less than design, were not provided in these reports.

The statistical design approach was based on mean settlements; maximum calculated values occasionally reached up to 2 m, for example for boreholes near fences at km 79.2 and 272.0. Areas with large actual borehole predictions and thus potential for substantial differential thaw settlement, the prime concern for pipe integrity, were included in IPL's geotechnical monitoring program. Seven thaw settlement sites were identified in IPL'S original monitoring program (IPL, 1984); these were located at kmp 2, 121, 222, 271, 366, 371 and 608.

Visual observations of surface settlement form an integral part of IPL's geotechnical monitoring program and are used to identify areas for detailed investigation of differential thaw settlement beneath the pipe. By the end of 1986, IPL's visual monitoring program had identified an additional 18 locations for detailed thaw settlement investigation (IPL, 1986). Additional ground temperature instrumentation has been installed at 5 of these locations. Three thermal fences (84-1, 85-7B and 85-12B), where surface settlements of over 60 cm have been recorded in the trench area and of over 50 cm elsewhere on the ROW, are included in these detailed thaw settlement investigations.

It should be stressed that settlements recorded at thermal fences by the Permafrost and Terrain Research and Monitoring Program are surface settlements; the program does not include monitoring of pipe movements. The surface settlements can not be directly compared to the design thaw settlements, since the time periods involved are not the same (3.5 yrs vs 30 yrs) and since the predictions relate to settlement beneath the pipe. As thaw depths progress beneath the pipe, it may then be possible to infer settlement of the soil beneath the pipe based on observed increases in surface settlement.

Thermal erosion susceptibility indices

The "Thaw Settlement Design Values" report (IPL, 1982f) also provides terrain settlement statistics calculated for each borehole for a pipe burial depth of 0.0 m. These settlements are therefore predictions of ground surface settlements after 30 years of pipeline operation. "Design" surface thaw settlements are not derived from these calculations for the pipeline segments designated above, only design settlements beneath the pipe since these were the principal concern for pipe design.

IPL's report on drainage and erosion control procedures (IPL, 1983) does however provide "thermal erosion susceptibility indices" (T.E.S) which are linked to anticipated surface thaw settlement. The ranges of surface settlement established for these indices were derived using the borehole thaw settlement data and were given as follows:

T.E.S. Index	Thaw Settlement Range (s = mean settlement)
0	no settlement
1	s<0.3 m
2	0.3 m </= s < 0.6 m
3	0.6 m </= s < 0.8 m
4	s>0.8 m

The T.E.S. indices are one of several design parameters evaluated for the assessment of drainage and erosion control requirements for each segment of the pipeline. From the tables provided in the drainage and erosion control report, the T.E.S. index established for the terrain at each of the 17 permafrost monitoring fences can be determined as follows:

T.E.S. Index	Sites
1	2A, 2B, 2C, 3A
2	1, 3B, 7A, 7B, 7C, 8A, 8B, 8C, 10B, 12B, 6
4	5A, 5B

A comparison of the recorded surface settlements (Table 4-5) with the corresponding T.E.S. indices can thus be made. Again this analysis involves comparing observations obtained after 2.5-3.5 years with predictions made for 30 years. This study revealed that in the trench area maximum surface settlement in excess of the predicted values had been recorded at 9 permafrost fences (1, 3A, 7A/B/C, 8B/C, 10B, 12B). In general, as the histograms in Figure 4-15 indicate, the predicted values are exceeded in localized pockets representing a small percentage of the terrain surveyed. However frequent small pockets are more likely to cause differential settlement problems than a layer of ice of uniform thickness. For the rest of the ROW localized areas of surface settlement in excess of the predictions have been observed at 4 fences (1, 3A, 8B, 8C).

5. OVERALL TERRAIN CONDITIONS AND PERFORMANCE

The comments made here regarding overall terrain conditions and performance are based upon a series of site and time-specific field observations and represent, therefore, a discrete rather than a continuous record of events on the pipeline right-of-way. These observations, however, provide a reasonably representative view of terrain response to pipeline construction and operation through 1988. In addition to field reports produced by members of the monitoring program (see Appendix Table B-1 for schedule of field visits), information on terrain conditions and performance is available from other sources as follows:

(1) Continuous records ("logs") of ditch conditions produced by IPL during construction.
(2) Borehole records ("logs") obtained by IPL during pre-construction geotechnical programs and during establishment of the EMR/INAC monitoring sites.
(3) Sequential right-of-way topographic surveys, undertaken at selected thermal monitoring sites at intervals from June 1984 to August 1987 (see Table 2-8).
(4) Sequential air photographic coverage of the right-of-way at intervals since 1983 (Table 5-1).
(5) Annual reports on monitoring of pipeline construction and operation, produced by IPL for INAC and NEB in November 1984 and 1985, and in each subsequent year of pipeline operation.
(6) Discussion with INAC and IPL staff.

A brief summary of terrain and the terrain types along the pipeline route is found in Chapter 2 of Volume I. Also in Volume I are reviews of the terrain related design concepts and mitigative approaches (e.g. route selection, thaw-settlement, slopes, drainage and erosion control, Chapter 3) and background on pipeline construction and operations (Chapter 4).

5.1 CONSTRUCTION PHASE (1984-1985)

5.1.1 Ground ice conditions

Excavation of the pipeline ditch permitted observation of ground ice morphology and distribution to a depth of 1 m for a range of geologic and geomorphic settings. In addition to sporadic scientific observations by EMR personnel, the continuous geotechnical ditch log for all construction spreads was made available by IPL. Sample data were recorded at 1 km intervals along the entire pipeline route. The ditch log for Spread 1 (km 0-190) contains the greatest amount of detail and is used here to attempt to characterize near-surface ground ice distribution along the northern segment of the pipeline. Since observations were made

TABLE 5-1. Summary of Norman Wells Pipeline aerial photography.

YEAR (Month)	SCALE BLACK & WHITE	SCALE COLOUR (# of locations)		SPONSOR
1983 (Aug)	1:10,000 (km 0-759)	1:4,000	(12)	Land Resources (INAC)
1984 (July)	1:10,000 (km 540-869)	1:5,000	(24)	Land Resources (INAC)
1985 (Aug)	1:10,000 (km 0-869)	1:5,000 1:10,000	(44) (2)	Land Resources (INAC) Terrain Sciences (GSC, EMR)
1986 (July)	1:10,000 (km 0-869)	1:4,000	(29)	Interprovincial Pipe Line
		1:5,000	(18)	Land Resources (INAC)
1987 (Oct)	1:10,000 (km 0-869)	-		Land Resources (INAC) Terrain Sciences (GSC, EMR)
1988 (Aug)	1:5,000 (km 0-869)			Interprovincial Pipe Line

Photography is available through the National Air Photo Library, Ottawa, Canada. The Alberta coverage was sponsored by the Terrain Sciences Division of Energy, Mines and Resources; the NWT coverage, by the Land Resources Division of Indian and Northern Affairs Canada in 1985 and 1987.

during mid-winter, the depth of seasonal thaw within the ditch could not be determined. Thus it is very probable that at least part of the ice recorded in the ditch log is of a seasonal rather than perennial nature.

Table 5-2 shows the distribution of ground ice recorded in the ditch log at one kilometre intervals along the pipe ditch (also called pipe trench) classified according to terrain type. Ice occurrence is high in each of the three major terrain types represented within this section of the pipeline route. Beneath lacustrine terrain units, ice was recorded at nearly 90% of sample localities, with visible ice recorded in 50% of cases. Ice occurrence appears to be more variable beneath areas characterized as moraine; 61% of sample localities in this terrain type had no record of ice while nearly 30% of localities had visible ice recorded. Ground ice exposed in ditch and side slope sections occurred in the form of discrete lenses and layers (Figure 5-1) as well as more irregular ice masses (Figure 5-2).

Table 5-3 shows ground ice distribution in relation to its enclosing earth materials. These represent visual observations only, and were not always described systematically. For example, some material listed as silt, sand or clay may actually be till. Similarly, it is likely that there are overlapping boundaries between, for example, silt and organic silt. In most cases, an approximate

TABLE 5-2. Ground ice distribution classified according to terrain type (km 0-190).

		GROUND ICE OCCURRENCE (%)						
TERRAIN TYPE	SAMPLE SIZE	NF	NB	N TOTAL	V 0-20%	V >20%	V TOTAL	NO RECORD
Alluvial	5 (2.6%)	20.0	20.0	40.0	-	20.0	20.0	40.0
Colluvial	3 (1.6%)	33.3	33.3	66.6	33.3	-	33.3	-
Eolian	3 (1.6%)	66.6	33.3	100.0	-	-	-	-
Glaciofluvial	6 (3.2%)	33.3	66.6	100.0	-	-	-	-
Lacustrine	86 (45.3%)	5.8	33.7	39.5	22.1	27.9	50.0	10.5
Lacustrine-Morainal	29 (15.3%)	3.5	37.9	41.4	20.7	10.3	31.0	27.6
Morainal	31 (16.3%)	-	9.7	9.7	16.1	12.9	29.0	61.3
Organic	9 (4.7%)	-	22.2	22.2	33.3	22.2	55.5	22.2
Bedrock	18 (9.5%)	-	16.7	16.7	27.8	-	27.8	55.6
TOTAL	190 (100.0%)		6.3	29.0	35.3	20.5	17.9	38.426.3

Source: IPL Ditch Log

Notes: 1. Sample points distributed regularly along trench at 1 km interval.
2. Ground ice classification after Pihlainen and Johnston, 1963.
N - Ice not visible
NF - Poorly bonded or friable frozen soils
NB - Well bonded frozen soils
V - Visible ice - less than 2.5 cm thick

Figure 5-1. Segregated ground ice layers in lacustrine sediments exposed in the ditch wall, km 98.1. (26/02/84).

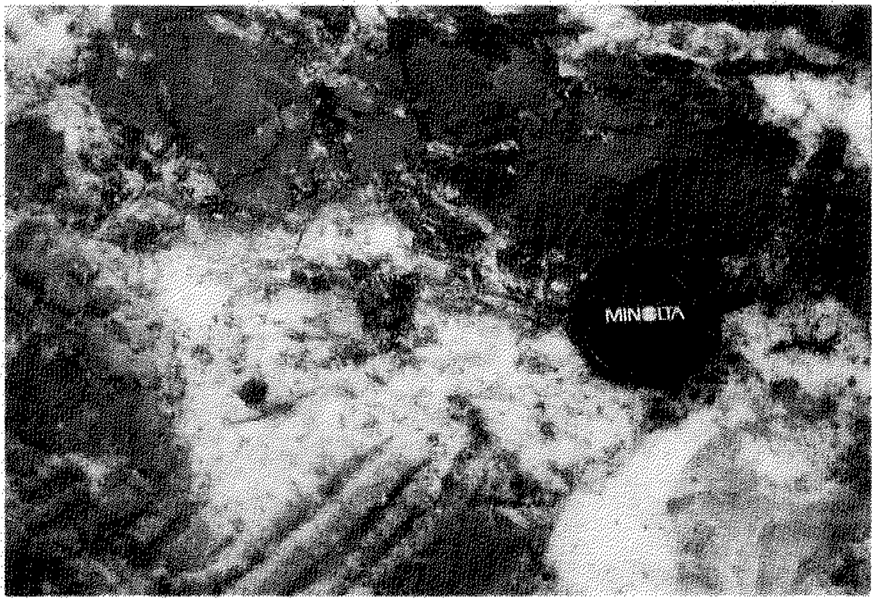


Figure 5-2. Irregular lenses and masses of ground ice in glacial till exposed in a side slope cut, km 133. (21/01/84).

Table 5-3a. Ground ice distribution classified according to enclosing earth materials: (a) upper ditch (km 0-190).

		GROUND ICE OCCURRENCE (%)						
MATERIAL TYPE	SAMPLE SIZE	NF	NB	N TOTAL	V (0-20%)	V (>20%)	V TOTAL	NO RECORD
Clay-silt	8 (4.2%)	-	37.5	37.5	50.0	-	50.0	12.5
Silt	23 (12.1%)	-	13.0	13.0	26.1	30.4	56.5	30.4
Silt-sand	26 (13.7%)	7.7	30.8	38.5	34.6	3.9	38.5	23.1
Sand	23 (12.1%)	34.8	56.5	91.3	-	-	-	8.7
Gravel	12 (6.3%)	33.3	-	33.3	-	-	-	66.7
Till	22 (11.6%)	-	50.0	50.0	9.1	-	9.1	40.9
Organic silt	48 (25.3%)	-	10.4	10.4	25.0	25.0	50.0	39.6
Organic	26 (13.7%)	-	7.7	7.7	19.2	46.2	65.4	26.9
Colluvium	2 (1.1%)	-	-	-	50.0	-	50.0	50.0
TOTAL	190 (100.0%)	7.4	23.7	31.1	20.5	16.8	37.4	31.6

Source: IPL Ditch Log
Notes: 1. Sample points distributed regularly along trench at 1 km interval.
2. Ground ice classification after Pihlainen and Johnston, 1963.

Table 5-3b. Ground ice distribution classified according to enclosing earth materials: (b) lower ditch (km 0-190).

		GROUND ICE OCCURRENCE (%)						
MATERIAL	SAMPLE SIZE	NF	NB	N TOTAL	V (0-20%)	V (>20%)	V TOTAL	NO RECORD
Clay-silt	10 (5.3%)	-	20.0	20.0	60.0	-	60.0	20.0
Silt	31 (16.3%)	-	32.3	32.3	22.6	22.6	45.2	22.6
Silt-sand	25 (13.2%)	4.0	36.0	40.0	40.0	4.0	44.0	16.0
Sand	32 (16.8%)	21.9	62.5	84.4	6.3	-	6.3	9.4
Gravel	13 (6.8%)	46.2	-	46.2	-	-	-	53.8
Till	52 (27.4%)	-	30.8	30.8	3.9	-	3.9	65.4
Organic silt	17 (9.0%)	-	5.9	5.9	35.3	35.3	70.6	23.5
Organic	6 (3.2%)	-	16.7	16.7	-	50.0	50.0	33.3
Colluvium	2 (1.1%)	-	-	-	50.0	-	50.0	50.0
Bedrock	2 (1.1%)	-	-	-	-	-	-	100.0
TOTAL	190 (100.0%)	7.4	31.1	38.4	17.9	9.0	26.8	34.7

Source: IPL Ditch Log
Notes: 1. Sample points distributed regularly along trench at 1 km interval.
2. Ground ice classification after Pihlainen and Johnston, 1963.

sediment and ground ice stratigraphy was recorded in the ditch log, enabling a division of the ditch into upper and lower units. As would be expected, there is a higher proportion of organic material in the upper part of the ditch, although within some terrain units the organic layer extended to the base of the ditch. A wide range of sediment types were encountered on this northern section of the pipeline route. Organic material, silt and sand predominate in the upper part of the ditch, while the higher proportion of till at depth suggests that these materials often form only a thin veneer.

Within the upper part of the ditch (Table 5-3a), visible ice was recorded at nearly 40% of sample points, most frequently in association with organic material and fine-grained sediments. More than 46% of organic samples, 30% of silt samples and 25% of organic silt samples had estimated volumetric ice contents in excess of 20%. In contrast, sand and gravel samples contained no visible ice and, while most of the sand samples were ice cemented, the majority of gravel samples were not observed to be associated with any form of ground ice. Similarly, 50% of till samples also were found to be ice cemented while most of the remainder had no recorded ice content. Data from the lower part of the ditch (Table 5-3b) indicate a generally lower visible ice content, possibly suggesting a transition through the aggradational ice layer which occurs just below the permafrost table. Visible ice contents are again highest in fine-grained sediments and organic materials, while over 65% of till samples and 53% of gravel samples had no recorded ice content.

These results are in broad agreement with those of Lau and Lawrence (1976) and Heginbottom et al. (1978), based upon the analysis of borehole logs from the Mackenzie Geotechnical Data Bank. They indicate that highest ice-contents occur in association with silt and organic silt within lacustrine terrain units. The generally high ice content of near-surface organic material also emphasizes its sensitivity to thermal or mechanical disturbance. More variable ice conditions occur within moraine units, and lowest ice contents are associated with coarse-grained alluvial and glaciofluvial sediments, and bedrock.

5.1.2 Terrain performance

Two aspects of the winter construction operation are likely to have a major effect on subsequent terrain performance: (a) grading of the right-of-way surface and reduction of slopes to the design angle and (b) excavation and backfill of the pipeline ditch.

Grading of the ditch centerline or grading and packing of snow on the travel area of right-of-way are intended to provide a stable and trafficable work surface from which construction activities may be carried out (Figure 5-3). Ideally, this should be achieved with minimum practicable width of grading and minimum disturbance to the surface organic layer. This material insulates underlying permafrost

Figure 5-3. Winter construction activities conducted on a packed snow surface, km 532, view north. (30/01/84).

mineral soil during the summer thaw period. The option of saving and replacing surface soils or organic materials, which is sometimes used in summer construction projects, is not feasible on a pipeline constructed during winter.

During the early phase of the 1983-1984 construction season, snowfall and snow depth were significantly below normal on Spread 1 (see Table 3-1c and Figure 3-2a), particularly between Norman Wells and Fort Norman (km 0-80). Partly as a result, the organic mat was damaged or removed completely along an estimated 15-25% of this segment of the right-of-way, in many cases, for the full width of the right-of-way rather than the ditch centerline and travel area only. Hummocky terrain was bladed to improve access (Chapter 4, Vol.I). Significant removal of organic materials also occurred further south, for example at km 789.2 and between km 807.2 and km 808.6, during levelling of hummocky terrain to improve trafficability. In these areas, the right-of-way crosses terrain characterized by peat plateau development, probably underlain by massive ice or ice-rich sediment.

In both cases, the possibility exists for subsequent adverse terrain performance, including thaw settlement and accelerated erosion. During the 1984-1985 construction season, winter snow depth along the pipeline route was near or above normal. This contributed to a reduction in the level of surface disturbance during packing and grading operations. Where grading extended across the ROW, seeding and fertilizing plans were revised to include the full ROW width.

More extensive grading is required to reduce steep slopes to their design angle (Table 3-6, Vol.I). Slope cuts are commonly associated with stream crossings, particularly in the northern two spreads where the pipeline route intersects a number of deeply incised stream valleys (Figure 2-2, Vol.I). In general, slope cuts on this line were excavated 1-5 m below grade and extended along the right-of-way for up to 100 m.

Excavation of the pipeline ditch results in a linear zone of intense terrain disturbance, varying from 0.8-2.0 m in width depending on the mode of excavation utilized. Three excavation modes were utilized on this project, wheel ditcher, backhoe/ caterpillar, and blasting. It should be noted that excavation mode varied considerably even within a one-kilometre section of the right-of-way in response to site-specific geologic conditions. In general, wheel ditchers were used on terrain units possessing a low boulder content (organic, lacustrine).

The wheel ditchers used (Figure 4-5, Vol.I) excavate a clean sided trench approximately 1.2 m deep and 0.8 m wide, and probably causes the least terrain disturbance of the three modes. Use of backhoes and large caterpillars (Figure 4-6, Vol.I) increases the degree of disturbance appreciably and widens the impacted zone to 1.5-2.0 m. This is particularly noticeable in areas underlain by saturated, unfrozen sediments, which slough into the trench during excavation. Blasting was rarely utilized, since the ditch is relatively shallow and most areas of the pipeline route are underlain by at least a veneer of unconsolidated sediment. In general, the degree of additional terrain disturbance resulting from the blasting operation appears to be negligible. The probability of adverse terrain performance in these areas is further reduced by the competent and thaw-stable nature of the earth materials involved.

Two significant terrain-related construction constraints were observed; first, the occurrence of ice-rich native spoil and, second, the variation in ditchability of surficial earth materials. In many areas, the ice content of materials excavated from the pipeline ditch was too high to allow it to be replaced in the ditch following pipe lowering. Instead, it was replaced by select (thaw-stable) backfill. Ditching rates varied considerably, depending on the character of surficial materials. Highest rates were achieved in areas of thick organic deposits, where excavation could be achieved entirely by the use of wheel ditchers. Rates were lower in areas characterized by well-cemented permafrost, and frequent delays were experienced in areas of bouldery till, where excavation was achieved by the use of backhoes, following preparation of the material by large caterpillars. Particularly slow progress was made in areas of wave-washed till surfaces, for example km 490-527, where several large boulder beaches were traversed.

5.2 POST-CONSTRUCTION PHASE (1984-1989)

Observations of post-construction terrain conditions and performance have been made along the entire pipeline since 1984 (Appendix Table B-1). In addition to specific studies at the instrumented sites described in Chapter 4 and 7, attention has focused upon:

(1) Monitoring of the physical condition of the right-of-way surface, especially in areas of potential adverse terrain response to disturbance identified during construction phase.
(2) Identification of actual and potential zones of enhanced surface erosion.
(3) Observation of surface stability, with particular regard to potential surface thaw settlement.
(4) Visual monitoring of stability of insulated and uninsulated slopes, particularly adjacent to stream crossings.
(5) Evaluation of mitigative measures and maintenance activities designed to reduce the terrain impact of pipeline construction and operation.

In all cases, it should be noted that the terms "terrain stability" and "slope stability" are used strictly within the context of observed geomorphic processes. No implication is intended regarding the engineering criteria or safety factors employed in slope design. The term "thaw settlement" refers to observed subsidence of the ground surface, rather than to any possible vertical movement of the pipe. An adverse terrain response is defined here as one which would be identified, by an IPL line patrol or INAC regulatory officer, as requiring remedial attention.

5.2.1 General right-of-way conditions

Terrain performance has now been monitored over five thaw seasons on sections of right-of-way constructed in winter 1983-1984, and over four thaw seasons on sections constructed in winter 1984-1985. Numerous site-specific instances of adverse terrain response have been identified by IPL, INAC and the Permafrost and Terrain Research and Monitoring Program. It should be emphasised, however, that these form very much the exception to the rule and account for less than 5% of the total length of the pipeline alignment. Instances of sub-optimal terrain performance highlighted in the following sections therefore represent problem situations rather than the norm. However, they provide site-specific case studies which can be used to better evaluate and mitigate terrain impacts in northern environments. Site specific conditions can also influence the viability of the entire pipeline system, as in a site specific pipe failure.

Observations to date suggest that the first few thaw seasons following construction are critical in terms of potential adverse terrain performance. This is due to four main factors:

(1) It is during this period that erosion control structures are first tested by spring snowmelt runoff and summer precipitation. Any shortcomings in the design or field implementation of these structures is likely to become readily apparent.
(2) Ditch subsidence due to the melt of ice-rich backfill or snow will occur almost immediately following the onset of summer thaw subsequent to winter construction. Subsidence may be accentuated by thermal and mechanical erosion of ditch material by flowing water.
(3) Increased surface erosion may occur during this period on areas of right-of-way where vegetation cover was partially or completely removed during construction.
(4) In areas of permafrost terrain, the geothermal impact of tree cover and ground vegetation clearance (in areas of newly-cleared right-of-way) and terrain disturbance during construction will affect surface stability during this period.

Climatic conditions have proved to be a major factor affecting terrain performance during the post-construction period. In particular, high intensity summer rainfall events have significantly influenced the nature and rate of geomorphic processes operating on and adjacent to the pipeline route. Increased rates and volumes of runoff have resulted in:

(1) saturation of near-surface sediments for prolonged periods, and ponding of water within closed basins (e.g. linear ponds formed along and adjacent to the pipeline ditch);
(2) sheetwash across overland sections of pipeline right-of-way, resulting in entrainment of exposed unconsolidated sediment, particularly select backfill;
(3) high channel discharge levels in streams and rivers, with associated high sediment loads and river bank erosion rates;
(4) possible raising of ground water tables in areas of karst terrain (e.g. near Bear Rock);
(5) possible decreases in stability, on both natural and pipeline-related slopes.

5.2.2 Surface stability

In this chapter, the term "surface stability" is used to denote the amount of vertical movement of the ground surface, due primarily to thaw settlement. The key issue of differential thaw settlement, and its potential effect on pipe integrity, is being addressed within the IPL monitoring program. Two types of surface subsidence have been noted on the right-of-way (a) settlement of backfill within the ditch and (b) more general subsidence of the right-of-way surface.

Ditch subsidence occurred along extensive stretches of the pipeline route, in spite of the construction of a 0.5-1.5 m high spoil berm above the buried pipe. By the summer of 1988, nearly 300 km or approximately 30% of the pipeline route had experienced some degree of ditch subsidence. Settlement in excess of 20 cm had occurred over about 80 km of the pipeline route (Wishart, 1988). In some cases, this subsidence reflects the use of ice-rich or snow-contaminated backfill during construction. In many areas, however, it may result primarily from the thaw consolidation of frozen, blocky backfill which possessed initially high void ratios. On level stretches of right-of-way, ditch line subsidence has resulted in the ponding of water within shallow, linear basins (Figure 5-4). In some instances, free drainage of these ponds has been impeded by the presence of spoil from mound breaks, pushed laterally across the right-of-way.

Figure 5-4. Water ponded along subsided ditch line, km 18 (05/06/84).

Areas of subsided and/or eroded ditch have been subject to an ongoing IPL maintenance program, designed to backfill and "re-roach" the ditch line. This has been accomplished in most cases by winter remedial work (Figure 5-5). During 1986, 48 km of ditch were backfilled using 64,000 m^3 of imported granular material (IPL, 1986). In 1987, 36.6 km of ditch was backfilled using 50,000 m^3 of imported material (IPL, 1987). In some areas of organic terrain, an ATV "Prairie Bobcat" has been used to fill and cover the ditch with peat excavated during construction (Figure 4-9, Vol.I).

Figure 5-5. Re-roached ditch line, km 596, view north (23/06/86).

More general thaw subsidence has affected part or all of the right-of-way at some localities. In all cases, this has occurred in areas known from borehole data or by observations made in the pipe ditch to be underlain by ice-rich permafrost. Topographic surveys completed at EMR/INAC instrumented sites between June 1984 and August 1987 indicate settlement ranging from 0-120 cm in the trench area, and from 0-100 cm over the remainder of the right-of-way (see Table 4-5). At several locations, hummocky thermokarst microrelief has developed on the right-of-way since pipeline construction. For example, at km 78 (Great Bear River South), microrelief of 75 cm to 1 m developed within one year of construction. At this locality, the right-of-way crosses an alluvial terrace underlain by ice-rich frozen silt (Figure 5-6).

Near km 80, a number of small near-circular thermokarst pits and ponds up to 3 m in diameter and 50 cm in depth have developed on the right-of-way surface (Figure 5-7). Thaw subsidence of the right-of-way surface has also been observed at km 245 and km 271. These sites are being monitored to determine future trends in surface stability. At the Great Bear River site, for example, sequential topographic survey data suggest that most subsidence occurred prior to the earliest survey, in August 1984, and that little surface change has occurred through fall 1987. Future thaw settlement at all locations underlain by ice-rich permafrost will be a function of the vertical distribution of ice beneath the surface. Since this may be highly irregular, with thick ice bodies sometimes occurring at depth, surface settlement rates may be both non-linear and difficult to predict.

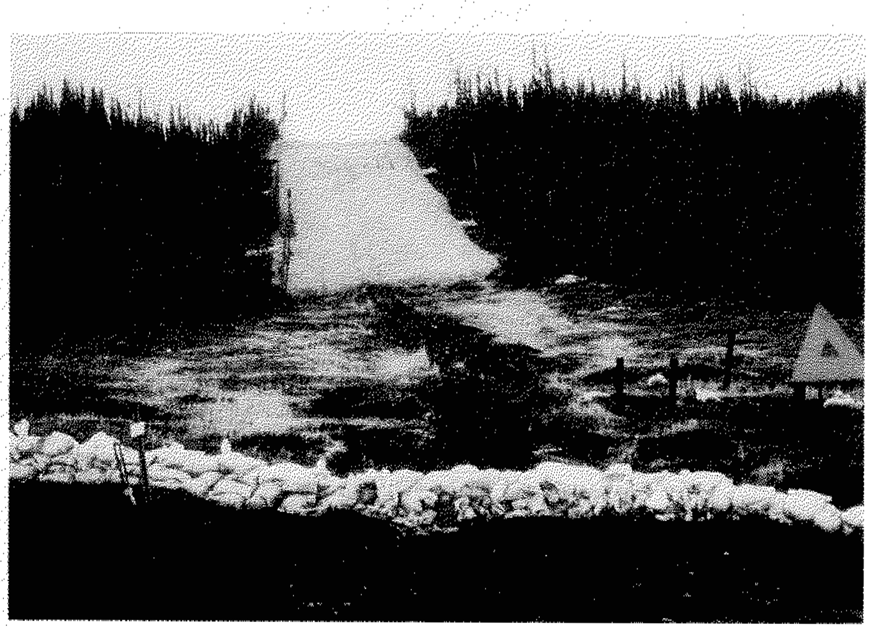
It should be noted that irregular subsidence of the wood chip surface has also been observed on several insulated slopes. This almost certainly reflects subsidence of the underlying mineral soil, rather than compaction and erosion of wood chips.

5.2.3 Surface erosion

The term "surface erosion" is used here to denote the physical removal of material from the right-of-way, primarily by flowing water. The main erosion control measures employed on this project are listed in Table 3-10 (Vol.I) and have been described by Wishart and Fooks (1985) and Wishart (1988). The primary function of erosion control structures is to divert flow off the right-of-way onto adjacent terrain. In areas where the potential for flow interception was high, lateral drainage ditches were constructed, either during construction or as a post-construction remedial measure. In addition, cross-drainage was facilitated by making breaks in the ditch mound, either at points where natural drainage courses intersected the right-of-way, or at regular (500 m) intervals in areas of poorly defined drainage.

Surface flow was designed to be diverted off the right-of-way by sandbag berms (Figure 5-8). These were placed in a diagonal or

a) Terrain conditions following construction (29/04/84).



b) Terrain conditions after first thaw season, showing development of hummocky thermokarst microrelief (19/09/84).

Figure 5-6. Alluvial terrace on south side of Great Bear River crossing, km 78, view south.

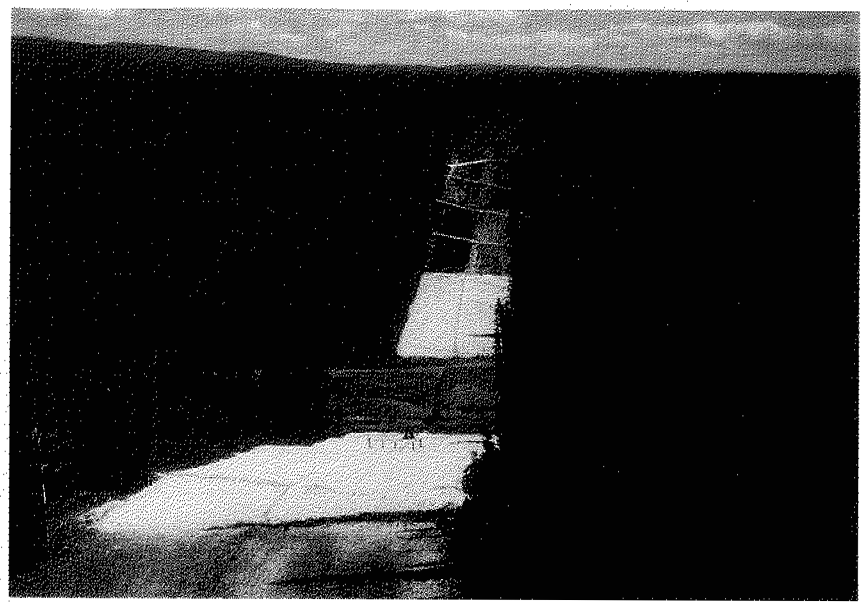
cycle during the first summer thaw period after placement. This heating is a result of microbial deterioration of the fresh wood chips, and is a well-known problem in the pulp and paper industry (Shields, 1967; Smith, 1973; Hulme, 1979; Springer, 1980). Microbial activity begins when the ambient temperatures in the wood chip layer rise to at least 5°C (Hulme, 1979). Maximum recorded temperatures occur in the centre of the wood chip layer after about 5 to 6 months and range from 16°C to 40°C (McRoberts et al., 1986).

All of the monitored wood chip layers on slopes along this pipeline have also indicated self-heating during the first few summer periods. About six slopes have shown persistent heating well into and sometimes throughout the winter months. Observations by IPL of snow melt patterns (Pick, 1987) has shown that persistent heating occurs in certain "hot spots" or pockets within the wood chip layer. It has been suggested by Pick (1987) that these "hot spots" are related to areas where the wood chip layer thicknesses exceed 1.4 to 1.5 m and where a large proportion of aspen/spruce wood chips may be present. Aspen has been known in the pulp and paper industry as a wood species that has exhibited persistent heating in outside wood chip storage piles. IPL's construction plans called for selective cutting in tree harvest areas to avoid use of aspen and birch as much as possible (Chapter 4, Vol.I).

6.1 PERFORMANCE OF WOOD CHIPS PLACED IN MARCH 1984

In March 1984, the first set of slopes along the pipeline right-of-way were insulated with wood chips. Temperature data from two of these slopes, Canyon Creek north slope and Great Bear River south slope, are presented in Figures 6-2 to 6-7 for the period March 1984 to June 1986. These slopes are "retard thaw" design. These data span three summer periods and two winter periods. Note winter data gaps up to two months (November and December) during the winter of 1984-85 and up to three months (middle of October to middle of January) during the winter of 1985/86. Except for the above noted gaps, data were manually recorded at both sites on a monthly basis by INAC/EMR personnel and supplemented by additional readings (seven per year) taken by IPL at Great Bear River. Figures 6-2 to 6-5 present data from the north slope of Canyon Creek (EMR/INAC instrumentation) including data from an off right-of-way datum cable. Figures 6-5 and 6-6 present data from the slope south of Great Bear River (IPL instrumentation, slope 29b).

Canyon Creek (INAC/EMR Site 84-2B, slope 3) is a unique site in that a thermal fence was installed across the right-of-way about the middle of the wood chip slope; this is the only government instrumented wood chip slope and it includes an off right-of-way cable. This thermal fence has three cables on the right-of-way and a control thermistor cable (Cable T4) in an uncleared area west of the right-of-way. The three cables on the right-of-way extend below a 1 m wood chip layer. At Great Bear River (slope 29b) there



a) Insulated slopes at Canyon Creek crossing, km 19.

b) Detail of wood chip insulation at Bosworth Creek, km 1.

Figure 6-1. Wood chip insulation.

Figure 5-7. Small thermokarst pits developed on the right-of-way surface at km 80 (08/06/85).

Figure 5-8. Erosion control berms constructed from sandbags, km 65.5, view south (06/06/84).

herringbone configuration, and were designed to have a slope of approximately 10 degrees. Spacing of berms along the right-of-way was determined by slope angle. The sandbags were designed to break down over a period of years, under natural ultraviolet radiation. Subsurface drainage along the ditchline was controlled by ditch plugs constructed from sandbags, bentonite and geotextile, or polyurethane and bentonite (Figure 5-9). These form low permeability barriers keyed into the ditch walls, which force water to the surface and block sediment movement along the ditch.

Surface erosion has occurred at numerous points along the pipeline alignment, generally resulting in the formation of gullies less than 10 cm in depth. Deeper erosion of the right-of-way occurred in 1984 at km 67, on the south flank of the Norman Range, and at km 78, on the north side of Great Bear River. In 1985, erosion affected the wood chip-covered slope on the north side of Blackwater River. Washout of ditch backfill occurred at several localities south of Fort Simpson. These four examples are described below in detail.

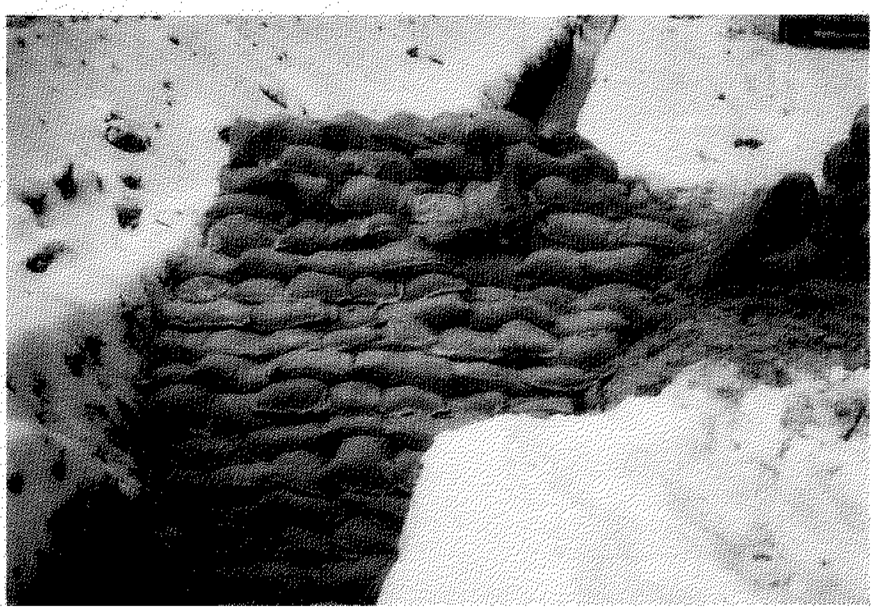


Figure 5-9. Bentonite ditch plug.

In most cases, erosion appears to have occurred due to a combination of high surface runoff and misplacement or misalignment of erosion control structures. The latter situation often resulted from the irregular subsidence of sandbag berms following snow melt and settlement or compaction of ditch fill (Figure 5-10). This problem was addressed during the second year of construction by supporting the berms on select backfill or sandbags in the ditch, and by adding an additional layer of sandbags to the berm to allow for residual subsidence (Wishart, 1988). In addition, identification of berm subsidence by IPL line patrols allowed prompt remedial action to be taken. Premature deterioration of the sandbags, designed to break down when exposed to natural ultraviolet radiation, may also have contributed to failure of these structures in some instances (Figure 5-11).

Erosion along the ditch line also occurred in areas where no drainage control structures were included in the original design. This was particularly apparent in 1985, when ditch erosion occurred along segments of the right-of-way characterized by long but gentle slopes, for example on the south side of Redknife Hills (km 610-700). Temporary maintenance work was carried out during the summer at some sites using backhoe-equipped Hagglunds ATVs. Where required, more comprehensive repair and remedial work was carried out during the following winter.

(i) Norman Range, km 67: (Frozen till and colluvium over bedrock)

This site is located on the southern flank of the Norman Range, between the pass to the east of Bear Rock and the Great Bear River crossing, and is underlain by permafrost. In this area, the right-of-way traverses an area of topographically irregular karst terrain, underlain by limestone with a mantle of till and/or weathered bedrock. Drainage lines are poorly developed and several closed basins occur in the vicinity. The route of the pipeline is generally parallel to the regional slope direction.

Following heavy precipitation and snowmelt runoff in May 1984, sustained water flow along the right-of-way became concentrated along the ditchline, resulting in the undermining and eventual destruction of a ditch plug. Unconsolidated select backfill within the trench was then washed out for a distance of approximately 200 m downstream of the initial point of flow interception, resulting in exposure of the pipe (Figures 5-12 and 5-13). This condition was identified by IPL and INAC staff in May, 1984, and the site was first visited by this author (D. Harry) on June 6, 1984. At that time, flow had decreased below peak conditions, but the high sediment content of runoff within the ditch suggested that erosion was still occurring. Downslope from the washout, the right-of-way was covered by an extensive alluvial fan of select backfill and native spoil, eroded from the ditch.

The specific cause of this erosion event remains uncertain. The catchment area above the point of flow interception is small (<1 km^2)

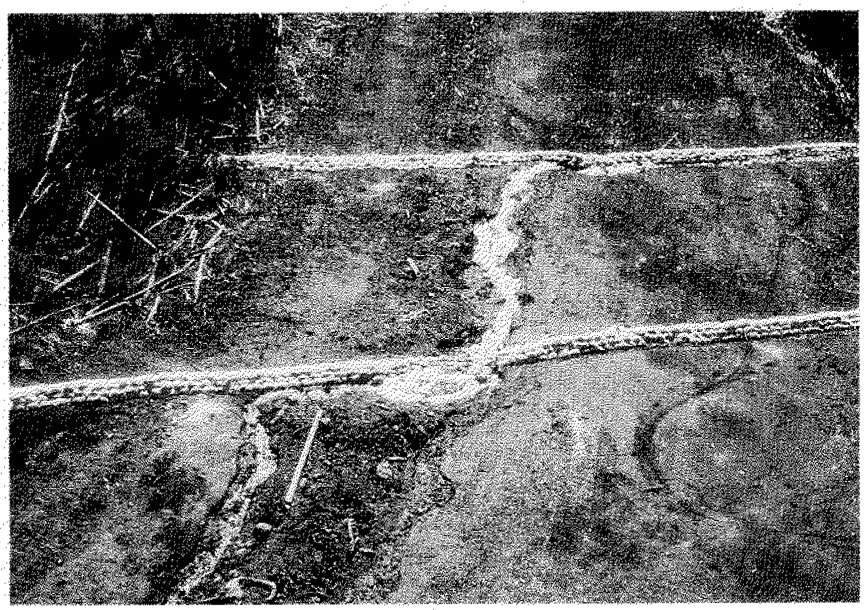


Figure 5-10. Minor erosion caused by failure of diversion berms, km 43, Vermilion Creek, northside (06/06/84).

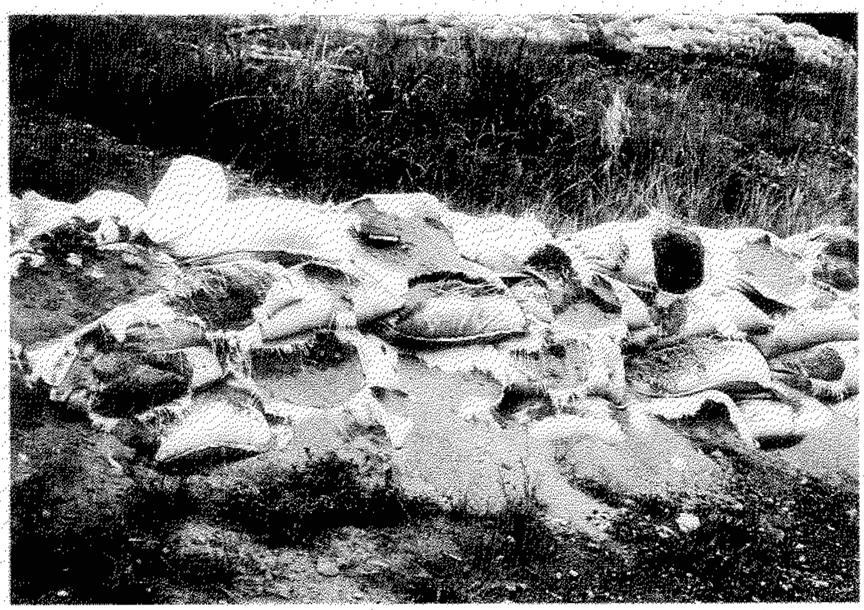


Figure 5-11. Premature decay of sandbags in diversion berm, km 26, Christina Creek (21/09/84).

Figure 5-12. Surface erosion at km 67, view north (26/09/84).

Figure 5-13. Surface erosion at km 67. Ground view showing exposed pipe and ditch plug (06/06/84).

and it is possible that natural runoff was augmented by discharge from high-level springs, activated by rising water tables within the limestone bedrock. In addition, it is clear that the distribution of diversion control structures was inappropriate, in that they tended to concentrate flow along the ditchline rather than remove it from the right-of-way. This may be due both to their original placement, and also to changes in berm configuration resulting from localized post-construction surface subsidence.

Temporary repair work, using vehicle access along the winter road alignment, was carried out during the 1984 thaw season to arrest erosion along the ditch. During winter 1985, permanent remedial work was undertaken. This consisted of the construction of a lateral drainage ditch, approximately 3 m wide and 1 m deep and faced with granular backfill, for a distance of 160 m downslope from the point of flow interception (Figure 5-14). This structure will collect water and guide it off the right-of-way along a short spur, surrounded by a rip-rap apron. The washout area was backfilled with material excavated from the new drainage ditch, mounded to form a berm 1.5-1.8 m high above the ditchline (Figure 5-15). In addition, two new diversion berms were constructed, including a V-shaped berm located upslope of the point of flow interception. Two new ditch plugs were also constructed to control water movement along the ditch itself.

Sequential observations of this site during the following five thaw seasons suggest that the remedial design has been adequate in controlling subsequent runoff events.

(ii) Great Bear River North, km 77-78 (IPL Slope 28A):

At this site, underlain by permafrost, the right-of-way follows a narrow, incised valley down to a terrace on the west bank of the Great Bear River. This routing was selected to avoid an archaeological site. The valley is cut in low ice-content sand and contains an ephemeral stream channel. During spring thaw in 1984, runoff eroded the toe of the side slope to the north of the right-of-way and triggered a series of mass flows (Figure 5-16). Sediment from the flows was redeposited further down the right-of-way and did not appear to enter Great Bear River.

Remedial measures carried out during the following winter consisted of the installation of a new ditch plug and reconstruction of a diversion berm at the point of flow interception. In addition, side-slope areas experiencing mass movement were covered with rip-rap extending into a rock and geotextile-lined lateral drainage ditch (Figure 5-17). A log berm was constructed along the drainage ditch to control high runoff events.

Subsequent observations suggest that the remedial work has been successful in controlling erosion on the north side of the right-of-way. However, small mass flows have also developed on the south side of the right-of-way. During monitoring in September 1988,

Figure 5-14. Restored right-of-way at km 67, view north.

Figure 5-15. Restored right-of-way at km 67. Ground view showing lateral drainage ditch, new erosion control structures, and re-roached ditch line (05/06/85).

Figure 5-16. Failing side slope undercut by ephemeral stream erosion, km 77 (north side of Great Bear River crossing). View south (20/09/84).

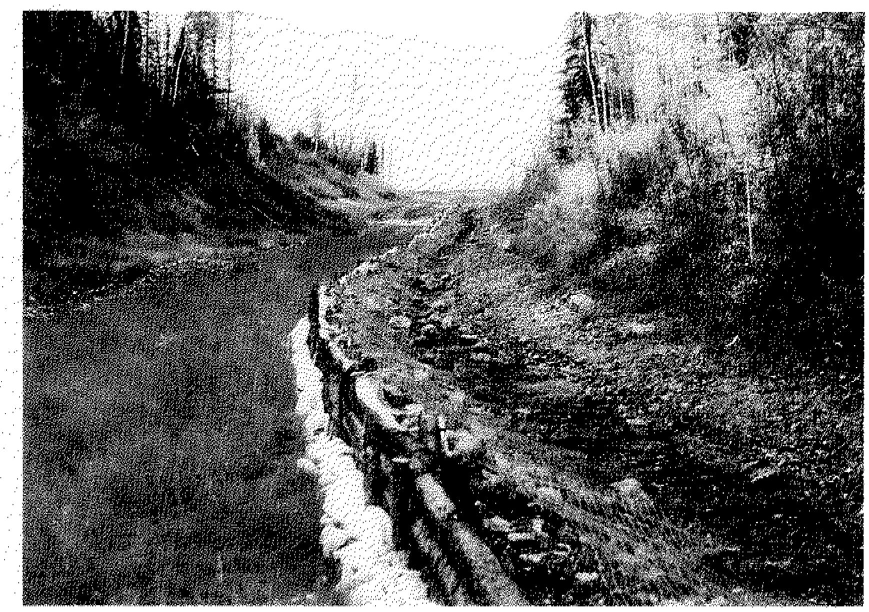


Figure 5-17. Restored right-of-way at km 77. View north, showing lateral drainage ditch and rip-rapped side slope (04/09/85).

the drainage ditch was observed to be capable of handling storm runoff.

(iii) Blackwater River North, km 225 (IPL Slope 66);

At this location, the right-of-way slopes steeply down to the north side of the Blackwater River floodplain. A cross slope also exists such that the west side of the right-of-way abuts the toe of a 20-30 degree side slope. The right-of-way slope is underlain by ice-rich, silty colluvium, and was therefore judged to be thaw sensitive in the pipeline design and covered by an insulating layer of wood chips 0.7-1.8 m in thickness.

In spring 1985, surface runoff along the west side of the right-of-way eroded wood chips and triggered a number of minor failures of the side slope (Figure 5-18). The flow crossed the pipeline midway down the slope and drained away towards Blackwater River. Wood chips mobilized by the flow were redeposited on the adjacent forested slope at distances of up to 200 m from the right-of-way. They did not enter any adjacent perennial water courses, including Blackwater River.

Repair work undertaken during summer 1985 included re-excavation of a lateral drainage ditch, lined with filter cloth, along the west side of the right-of-way (Figure 5-19). During the following winter, the ditch was filled with coarse rip-rap. Trees were cut back from the edge of the failing side-slope, debris removed and the slope re-graded. This remedial program has been partly successful in reducing further right-of way and side slope erosion. However, field observations in June 1986 suggest that water flowing beneath the filter cloth and rip-rap may continue to undermine both the wood chip pile and side-slope toe (Figure 5-20). This site is thus likely to require a continued program of maintenance activities.

(iv) km 560-880:

Surface erosion on long, gentle, slopes caused by water flowing down the ditchline proved to be a low-level but widespread maintenance problem during the 1985 thaw season, particularly on the southern part of the pipeline route. For example, several washouts occurred between km 600 and km 687, between which points the pipeline route rises to the south at approximate grades of 1-4% (Figure 5-21). Terrain in this area consists predominantly of a variable thickness of peat overlying till. In most cases, erosion was confined to the ditch line; however, in the absence of ditch plugs or diversion berms, significant quantities of backfill were removed by the low velocity but high volume flow and in some cases the pipe was exposed.

In order to arrest erosion, temporary plugs were inserted into the ditch. A variety of materials was utilized, including straw

Figure 5-18. Erosion of side slope and wood chip cover at km 225 (north side of Blackwater River crossing). View south, showing initial stages of restoration work (08/06/85)

Figure 5-19. Restored right-of-way at km 225. View south, showing lateral drainage ditch lined with geotextile and filled with coarse rip-rap (21/06/86).

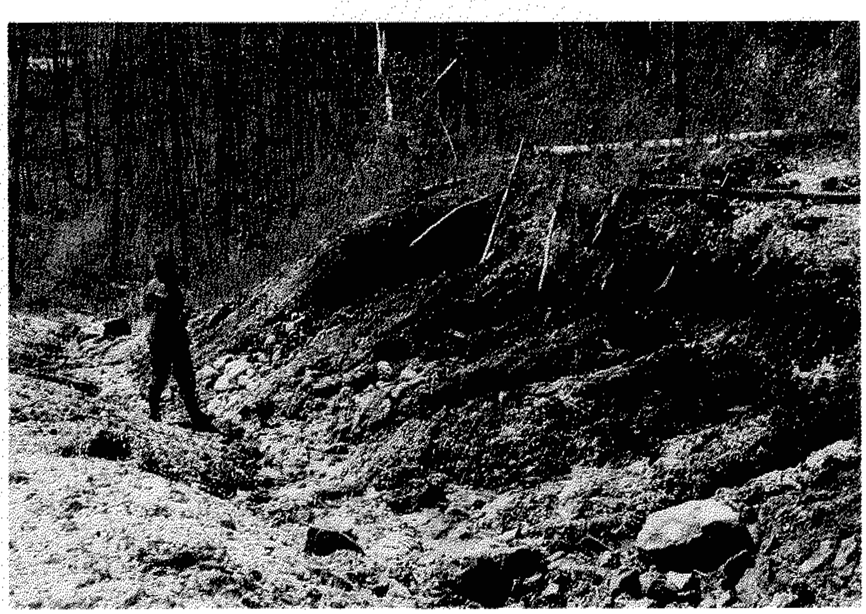


Figure 5-20. Side slope failure at km 225, view south (21/06/86).

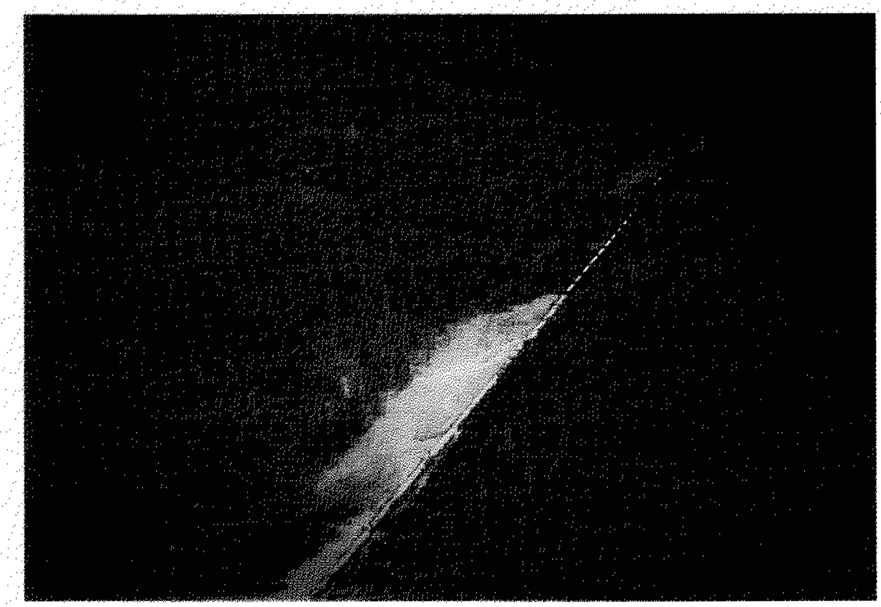


Figure 5-21. Alluvial fan produced by erosion of trench backfill, km 600. Water flow on low-angle slope became concentrated along ditch line (07/06/85).

bales, soil, and lengths of cut timber ("stick plugs"). Subsequently, a number of diversion berms have been placed across the right-of-way in areas which experienced erosion in 1985. At some localities, temporary plywood erosion control structures have been utilized in lieu of conventional sandbag berms (Figure 5-22). These check dams and flow diversion structures have functioned well since 1985. It is interesting to note that the area experienced no significant erosion problems following record-breaking 24-hour precipitation events in July 1988 (as recorded at stations 20-60 km from the pipeline route).

5.2.4 Erosion at stream crossings

Right-of-way erosion and mass movement on approach slopes (including loss of wood chips) has occurred at several stream crossings, as a result of high water events and, in some cases, insufficient streambank protection. Four case studies are described in detail below. At a few localities, water levels have been further raised as a result of downstream ice jams, or the presence of residual icings. At some crossings, the situation has been compounded by ditch subsidence across the active floodplain. This has resulted in the formation of embayments in the streambanks and the erosion of backfill by turbulent eddies, to produce deep pools on either side of the watercourse (Figure 5-23). The incidence of both subsidence and ponding has decreased between 1985 and 1988 as a result of restoration programs to refill areas of sunken ditch and armour unprotected streambanks. Natural infilling of subsided floodplain and stream ditch is also likely to occur as a result of sediment redistribution during flood events.

(i) Seagram Creek (km 168):

In Spring 1984, the south bank of the Seagram Creek crossing was undermined, resulting in the collapse and subsequent erosion of the slope toe (Figure 5-24). Terrain at the crossing consists of a veneer of lacustrine silt and clay overlying till. This occurrence may be attributed to the combination of two factors. First, the north side of the crossing was not protected by rip-rap as specified in the design and, second, Seagram Creek experienced a major flood event during this period. The magnitude of this event was marked by the stranding in trees of sandbag remnants, eroded from the pipeline crossing area, at elevations of up to 3 m above floodplain level. No precipitation records exist for this location at the current time. Remedial work on this slope, consisting of the installation of rip-rap and backgrading of the slope, was carried out by a backhoe-equipped Hagglunds ATV (Figure 5-25). Detail of the slope toe restoration is shown in Figure 5-26. (To minimize surface disturbance during this summer restoration, work crews were flown back and forth to the nearby Little Smith Remote Maintenance Base.)

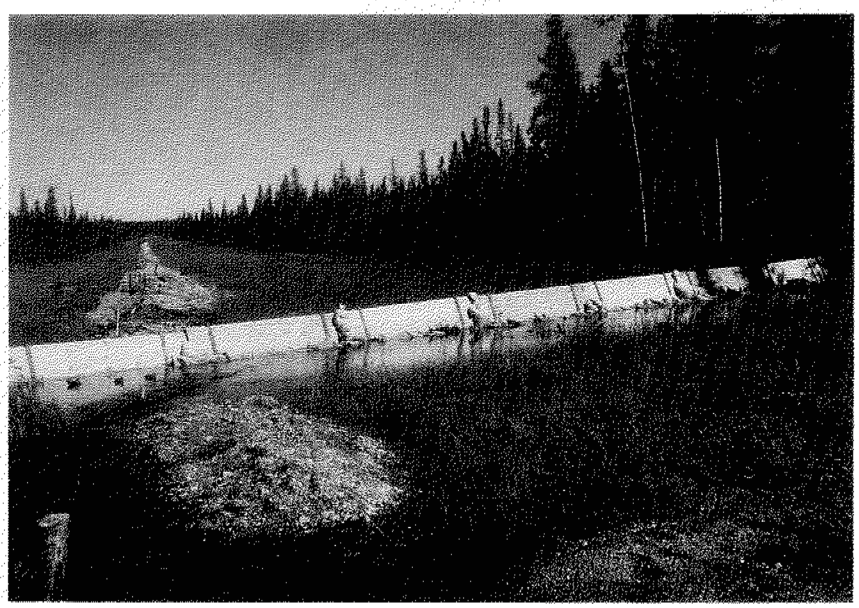


Figure 5-22. Plywood diversion berm, km 597, view north (23/06/86).

Figure 5-23. Ditchline subsidence across active floodplain, south side of Prohibition Creek, km 32 (21/09/84).

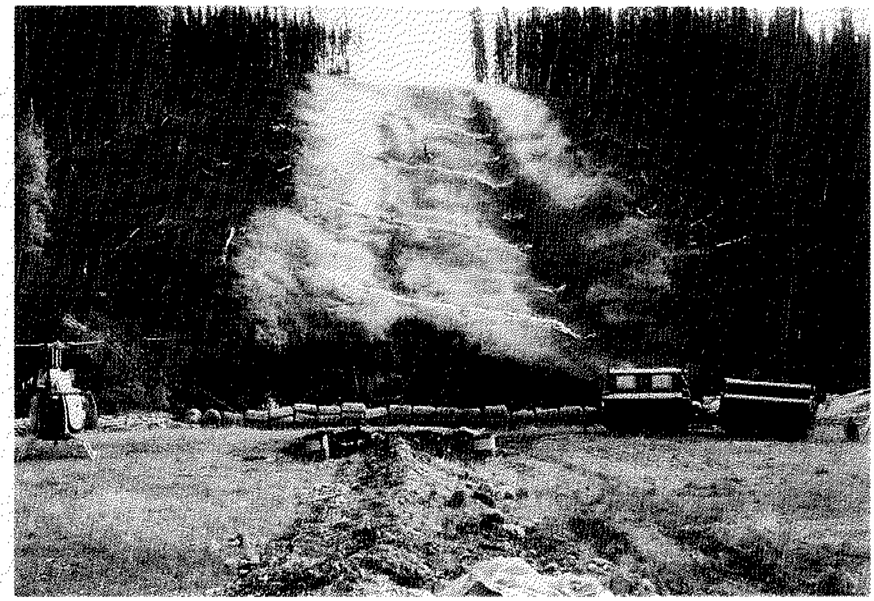
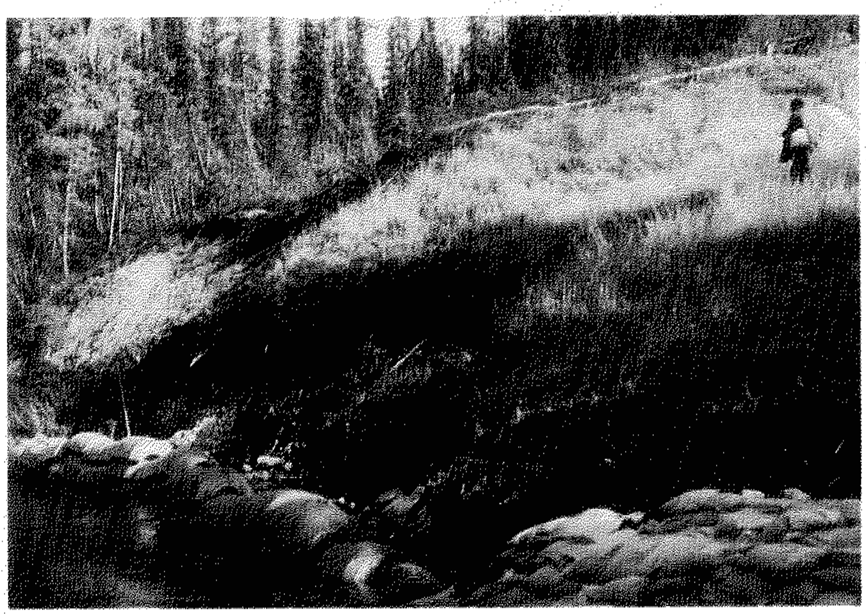


Figure 5-24. Slope toe failure, south side of Seagram Creek crossing, km 168 (19/09/84).

Figure 5-25. Remedial work in progress at Seagram Creek, km 168 (22/09/84).



a) During initial phase of remedial work (19/09/84).

b) Following remedial work (06/06/85).

Figure 5-26. Detail of slope toe, south side Seagram Creek, km 168.

(ii) Unnamed Creek (km 133):

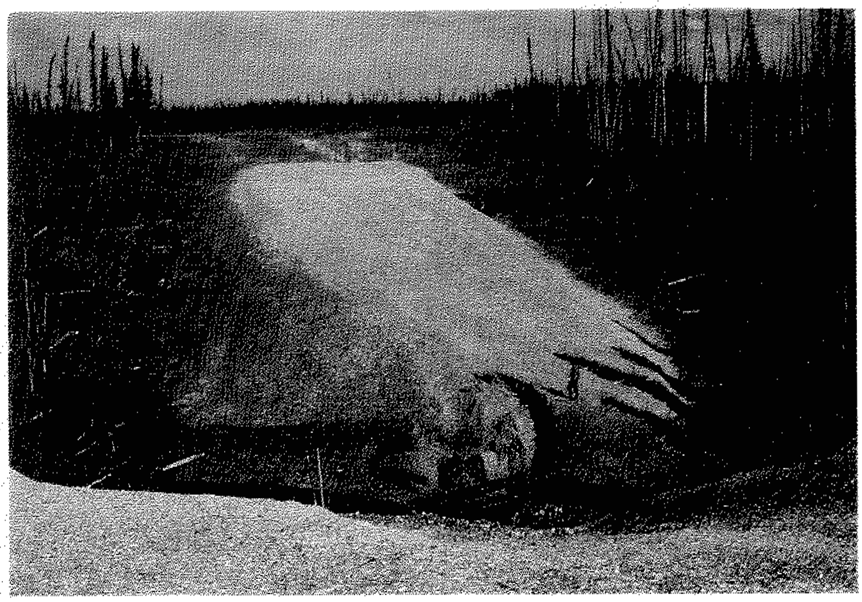
At localities where slopes approaching stream crossings are insulated by wood chips, high water levels have occasionally resulted in flotation and removal of wood chips. For example at km 133 (Unnamed Creek), a combination of flotation and erosion of wood chips occurred on the northern bank of a minor water crossing in June 1986. This undermined the wooden crib structure, resulting in further slumping and loss of wood chips (Figure 5-27a). Remedial work in winter 1986-87 consisted of replacement of the wood chips, repair to the cribbing and addition of new rip-rap on the streambank (Figure 5-27b).

(iii) Hodgson Creek (km 305):

On about June 25, 1986, the Hodgson Creek catchment north of Wrigley received approximately 56 mm of rainfall over a 24-hour period (measured at Mount Gaudet fire tower, approximately 8 km west of the pipeline crossing). This exceptional storm compares to an estimated 100-year return 24-hour maximum precipitation of 60 mm (Burns, 1974). High runoff levels resulted in the main stream channel changing its course and eroding part of the right-of-way in the vicinity of the pipeline crossing. In addition, part of the stream discharge broke through a meander neck and intercepted the right-of-way some distance south of the crossing. The flow followed the right-of-way for approximately 200 m northward before being diverted westward.

This situation raised two concerns; first, the new main channel was actively eroding the north bank of the crossing and, second, water was flowing along the right-of-way and eroding the ditch south of the sag point, that is, beyond the zone of deep burial adjacent to the crossing. A major remedial program was implemented in March 1987, based on the recommendations of a river engineering study commissioned by IPL. This consisted of (a) construction of a large, arcuate berm composed of coarse-grade rip-rap on the north side of Hodgson Creek (Figure 5-28a), (b) construction of a series of smaller diagonal berms on the south side of the crossing to divert water flow off the right-of-way and, (c) lowering of the pipeline throughout the floodplain area to eliminate scour problems which could result from any further migration of the main stream channel.

In July, 1988, the same area received approximately 63 mm of rainfall in a single storm, thus probably approaching or exceeding the predicted 100-year maximum 24-hour precipitation for the second time in three years. The resulting flood destroyed part of the major river training structure on the north side of the crossing (Figure 5-28b) and also broke through several of the diversion berms designed to control flow along and across the right-of-way on the south side of the crossing. Further remedial work in winter 1988-1989 consisted of deep re-burial of the pipe adjacent to the crossing, and reconstruction of the crossing itself, burying the new pipe to 3 m. This sequence of events highlights the difficulty in adequately



a) Collapsed cribbing and wood chip loss (21/06/86).

b) Restored slope (15/06/86)

Figure 5-27. North side of Unnamed Creek, km 133.

a) View in June 1987.

b) View in September 1988, showing partial destruction of berm during flood event of July 1988.

Figure 5-28. River training structure on north side of Hodgson Creek crossing (km 305), build following flood event of June 1986.

predicting and designing for storm runoff events in the Mackenzie Valley.

(iv) Ochre River (km 286):

During the same storm-related flood event that affected Hodgson Creek in July 1988 (Westerman and Burke, in prep), high water levels in Ochre River resulted in migration of the south bank at the pipeline crossing, by up to 30-50 m, and exposure of the pipe in the new main channel of the river. Exposed pipe was detected July 26. Earlier photographs on July 8 indicate that the channel had eroded at that time, however, the pipe was not visible in the sediment-rich flood waters. Temporary remedial work consisted of covering the pipe by hand work and with helicopter-transported sandbags, to eliminate further abrasion of the pipe by boulders entrained by the flood discharge. IPL monitored the pipe frequently (approximately every 3 days) throughout the remainder of the summer. The water crossing was rebuilt in winter 1988-1989 with new pipe buried at approximately 3 m depth.

5.2.5 Slope stability

The geomorphic stability of uninsulated slopes along the pipeline alignment has been assessed solely by observation of sediment mass movement, tension cracks, and displacement of mitigative structures, for example slope toe cribbing. IPL has instrumented a number of slopes to measure ground temperature and pore-water pressure.

Mass movement features were observed on several side slopes early in the spring following construction, for example in June 1985 at km 65-66 (Figure 5-29), but stabilized rapidly as moisture supply decreased and vegetation cover spread. In summer 1986, water flow along the "shoo fly" at km 273 undercut the side slope. Remedial measures consisted of construction of a rip-rapped drainage ditch and placement of wood chips on the side slope behind a retaining wall.

Movement of material on stream crossing approach slopes occurred in 1984 at km 732 (Kakisa River, south side), in 1985 at km 577 (Jean Marie Creek, north side), and in 1986 at km 286 (Ochre River, north side). Movement was triggered either by seepage of water from areas adjacent to the right-of-way, or by percolation of water along the ditchline. At Kakisa River and Jean Marie Creek, classic bimodal flow features developed, consisting of a steep, 1-2 m high headwall and a gently inclined tongue of transported debris. At Kakisa River, the debris tongue included large rafts of material carrying an intact vegetation mat (Figure 5-30), while at Jean Marie Creek the flow involved movement of fluidized granular sediment (Figure 5-31). Winter remedial work undertaken at each site included modification to drainage control structures, designed to reduce water supply to the slope, and regrading of the slope.

Figure 5-29. Minor side-slope failure and bimodal flow feature, km 65 (06/06/84).

Figure 5-30. Mass flow feature on south side of Kakisa River crossing, km 732 (25/09/84).

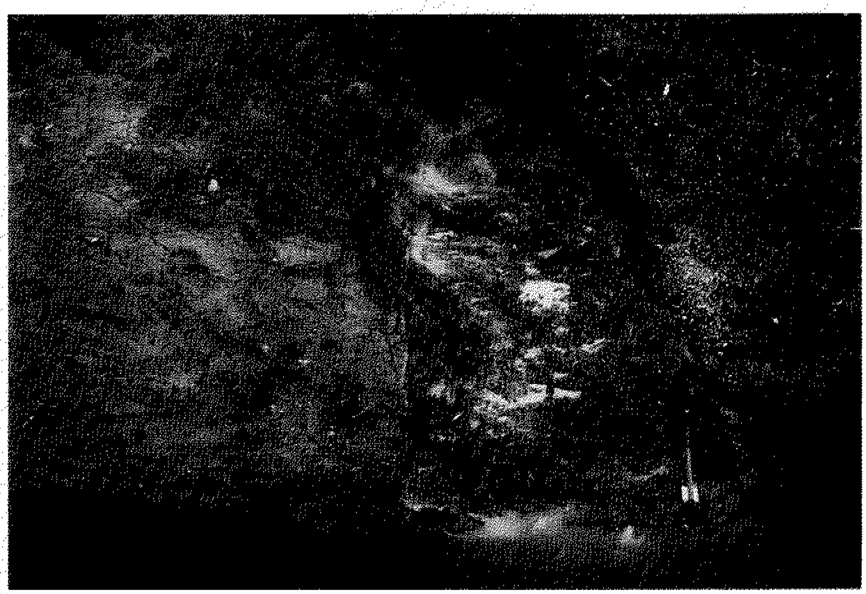


Figure 5-31. Mass flow feature on north side of Jean-Marie Creek crossing, km 577 (07/06/85).

5.2.6 Seismicity

Three earthquakes have occurred in the Nahanni area since pipeline operations began. Two large magnitude earthquakes occurred in 1985 near the North Nahanni River about 70 km west of the pipeline and another occurred in 1988 (magnitude 6.6 on 5 October 1985, magnitude 6.8 on 23 December 1985, and magnitude 6.0 on 25 March 1988). These events were unprecedented for this region and the December 1985 event is the largest earthquake ever known in the eastern part of the Canadian Cordillera (Wetmiller et al., 1988). The October 1985 quake triggered a rock avalanche, the fourth largest landslide in Canada (Evans et al., 1987).

The October 1985 event was predicted to have imposed sustained accelerations on the Norman Wells pipeline which were essentially equal to those of the design probable event (DPE) (McRoberts et al., 1986). IPL inspected the right-of-way, especially slopes, immediately after the event; no damage was observed. No damage was reported following the December 1985 and March 1988 quakes.

Seismic zoning for building code purposes in the eastern Cordillera north of 60°N needs reassessment. Zoning in the eastern Cordillera of British Columbia and Alberta may also need revision (Wetmiller et al., 1988).

6. THERMAL PERFORMANCE OF WOOD CHIP INSULATION (1984-1988)

The overall design and mitigative approaches for slopes are presented in Chapter 3 of Volume I. This chapter focuses on the evaluation of one specific mitigative measure from a thermal perspective.

In summary, the Norman Wells Pipeline traverses many slopes; over 165 of the slopes required geotechnical evaluation and design (McRoberts et al., 1985, 1986; Hanna and McRobert, 1988). The main mitigative approaches developed as a result of the geotechnical studies and analyses were:

(a) "prevent thaw"
(b) "retard thaw" and
(c) "cut back".

Interprovincial Pipe Line Ltd. (IPL) assessed several methods to insulate slopes including gravel, wood chips, styrofoam and thermosyphons (McRoberts et al. 1985).

IPL proposed the use of freshly harvested wood chips as a means of insulating 55 cleared slopes along the pipeline right-of-way (Table 6-1) because of their availability and their ease of use in cold weather. The use of wood chips to insulate and reduce thaw in permafrost has been discussed by Pufahl and Morgenstern (1979), McRoberts et al. (1985, 1986), Pick (1987) and Hanna and McRoberts (1988). Design advantages, disadvantages and solutions for wood chip use are summarized in Table 3-7 (Vol.I p.49). Stability and surface movements on wood chip covered slopes are discussed in the previous chapter (e.g. Figure 5-27). There is also one wood chip side slope off the right-of-way on the "shoo fly" at km 273.

Based on the concerns of several groups as to the performance of wood chips as an insulation, IPL proposed and implemented a monitoring program to ensure stability of the frozen slopes and to compare design thaw depth progression with measured thaw depths. Temperature data from 28 wood chip covered slopes have been collected by a joint monitoring program involving IPL, INAC and EMR (27 IPL instrumented slopes, 1 government instrumented slope). In 1985, INAC requested the assistance of NRC to assist them in the evaluation of the performance of the wood chips as an insulation on permafrost. Results of the overall permafrost and terrain monitoring program are reviewed annually. These data are considered proprietary until January 1, 1990.

This chapter provides comments on temperature data from three ice-rich slopes insulated with wood chips during construction of the pipeline. The data (monthly) presented here are from the government test site at Canyon Creek (Burgess 1987; Site 84-2B illustrated in the foreground of Figure 6-1a) and previously

TABLE 6-1. Thaw-sensitive slopes on the Norman Wells Pipeline insulated with wood chips.

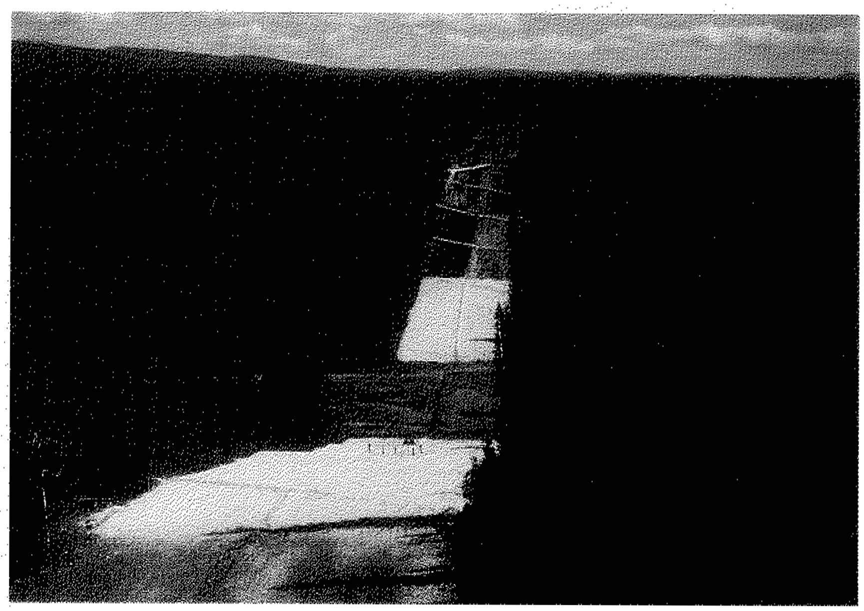
Slope/Name[1] No.		Location (kmp) (start)	Slope/Name No.		Location (kmp) (start)
1	Bosworth Ck.N	0.3	63	Steep Ck. S.	194.9
2	Bosworth Ck.S	0.4	66	Blackwater R.N	224.4
3	Canyon Ck. N	19.2	66	Blackwater R.N	224.8
4	Canyon Ck. S	19.4	71	Unnamed Ck. N	264.2
7	Francis Ck. N	23.0	73	Unnamed Ck. N	271.4
11	Helava Ck. N	25.6	74	Unnamed Ck. S	271.6
12	Helava Ck. S	25.7	75	Unnamed Ck. N	273.5
14	Christina Ck. S	26.6	76	Unnamed Ck. S	273.6
16	Prohibition Ck. S	32.3	77	Unnamed Ck. N	275.5
28	Gt. Bear River N.	78.4	78	Unnamed Ck. S	275.6
29A	Gt. Bear River S.	78.8	79	Unnamed Ck. N	279.0
29B	Gt. Bear River S.	79.2	80	Unnamed Ck. S.	279.3
30	Unnamed Ck. N.	84.4	82	Ochre River S.	286.6
31A	Unnamed Ck. S.	84.5	84	Unnamed Ck. S.	311.7
32A	Slope N.	93.2	86	Unnamed Ck. S	313.1
32B	Slope S.	93.3	87	Unnamed Ck. N	313.5
33	Unnamed Ck. N.	94.1	88	Unnamed Ck. S.	313.6
34	Unnamed Ck. S.	94.2	89	Unnamed Ck. N.	317.0
35	Unnamed Ck. N.	103.1	91	Unnamed Ck. N.	317.9
36	Unnamed Ck. S.	103.2	92	Unnamed Ck. S.	318.1
44	Unnamed Ck. N	133.6	96	Unnamed Ck. S.	320.6
45	Unnamed Ck. S.	133.7	98	Smith Ck. N.	325.1
47	Little Smith Ck.N.	159.5	99	Smith Ck. S.	325.3
48B	Little Smith Ck.S.	160.1	109	Unnamed Ck. S.	351.9
55	Unnamed Ck. S.	182.2	112	Riv.B.T. Mtn. N	352.3
61	Unnamed Ck. S	191.2	123	Unnamed Ck. N.	403.7
62	Steep Ck. N.	194.4	123A	Unnamed Ck. S.	403.8
			142	Mackenzie R. S.	529.6

1. Abbreviations: Creek (Ck), Great (Gt), North (N), South (S), River Between Two Mountains (Riv.B.T.Mtn)

Note: North and South refer to pipeline north to south positions only.

presented data from IPL instrumented slopes at Great Bear River (Figure 5-6) and Mackenzie River (from IPL 1986 Annual Monitoring and Surveillance Report to the Northwest Territories Water Board based on readings taken by both IPL and government). NRC will be preparing a report to be released in 1990 (a) on data obtained from additional instrumentation placed at Canyon Creek to study latent heat effects and heat flux in the wood chip layer and (b) reviewing the wood chip self-heating phenomenon from selected IPL instrumentation at 15 other slopes.

Wood chips were placed on slopes along the pipeline right-of-way at the end of the pipeline construction periods in March 1984 and March 1985, depending on the construction spread in which the slope was located. The temperature measurements indicated that generally all of the wood chip layers have undergone a self-heating



a) Insulated slopes at Canyon Creek crossing, km 19.

b) Detail of wood chip insulation at Bosworth Creek, km 1.

Figure 6-1. Wood chip insulation.

cycle during the first summer thaw period after placement. This heating is a result of microbial deterioration of the fresh wood chips, and is a well-known problem in the pulp and paper industry (Shields, 1967; Smith, 1973; Hulme, 1979; Springer, 1980). Microbial activity begins when the ambient temperatures in the wood chip layer rise to at least 5°C (Hulme, 1979). Maximum recorded temperatures occur in the centre of the wood chip layer after about 5 to 6 months and range from 16°C to 40°C (McRoberts et al., 1986).

All of the monitored wood chip layers on slopes along this pipeline have also indicated self-heating during the first few summer periods. About six slopes have shown persistent heating well into and sometimes throughout the winter months. Observations by IPL of snow melt patterns (Pick, 1987) has shown that persistent heating occurs in certain "hot spots" or pockets within the wood chip layer. It has been suggested by Pick (1987) that these "hot spots" are related to areas where the wood chip layer thicknesses exceed 1.4 to 1.5 m and where a large proportion of aspen/spruce wood chips may be present. Aspen has been known in the pulp and paper industry as a wood species that has exhibited persistent heating in outside wood chip storage piles. IPL's construction plans called for selective cutting in tree harvest areas to avoid use of aspen and birch as much as possible (Chapter 4, Vol.I).

6.1 PERFORMANCE OF WOOD CHIPS PLACED IN MARCH 1984

In March 1984, the first set of slopes along the pipeline right-of-way were insulated with wood chips. Temperature data from two of these slopes, Canyon Creek north slope and Great Bear River south slope, are presented in Figures 6-2 to 6-7 for the period March 1984 to June 1986. These slopes are "retard thaw" design. These data span three summer periods and two winter periods. Note winter data gaps up to two months (November and December) during the winter of 1984-85 and up to three months (middle of October to middle of January) during the winter of 1985/86. Except for the above noted gaps, data were manually recorded at both sites on a monthly basis by INAC/EMR personnel and supplemented by additional readings (seven per year) taken by IPL at Great Bear River. Figures 6-2 to 6-5 present data from the north slope of Canyon Creek (EMR/INAC instrumentation) including data from an off right-of-way datum cable. Figures 6-5 and 6-6 present data from the slope south of Great Bear River (IPL instrumentation, slope 29b).

Canyon Creek (INAC/EMR Site 84-2B, slope 3) is a unique site in that a thermal fence was installed across the right-of-way about the middle of the wood chip slope; this is the only government instrumented wood chip slope and it includes an off right-of-way cable. This thermal fence has three cables on the right-of-way and a control thermistor cable (Cable T4) in an uncleared area west of the right-of-way. The three cables on the right-of-way extend below a 1 m wood chip layer. At Great Bear River (slope 29b) there

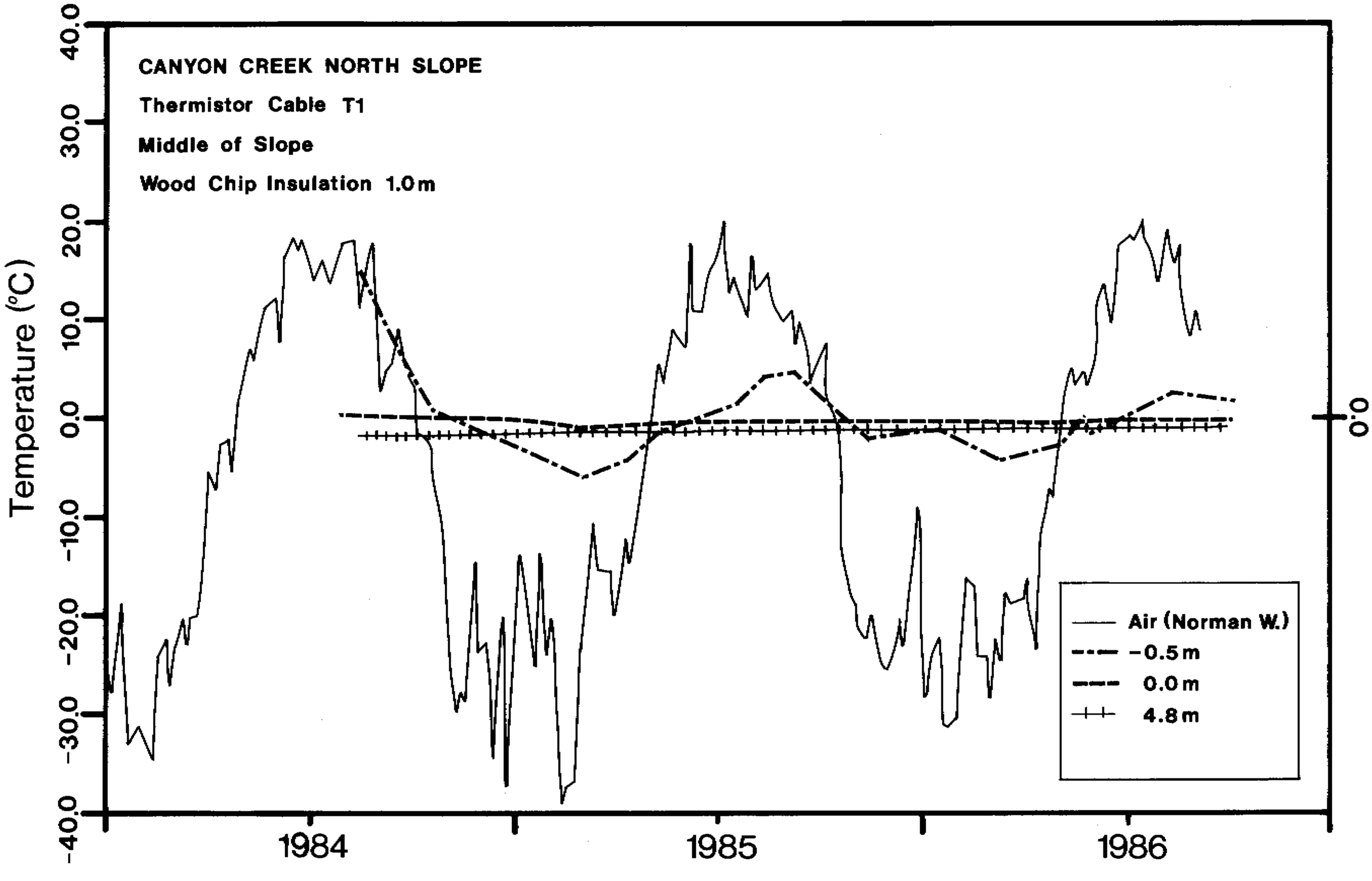


Figure 6-2. Canyon Creek North slope (84-2B) cable T1.

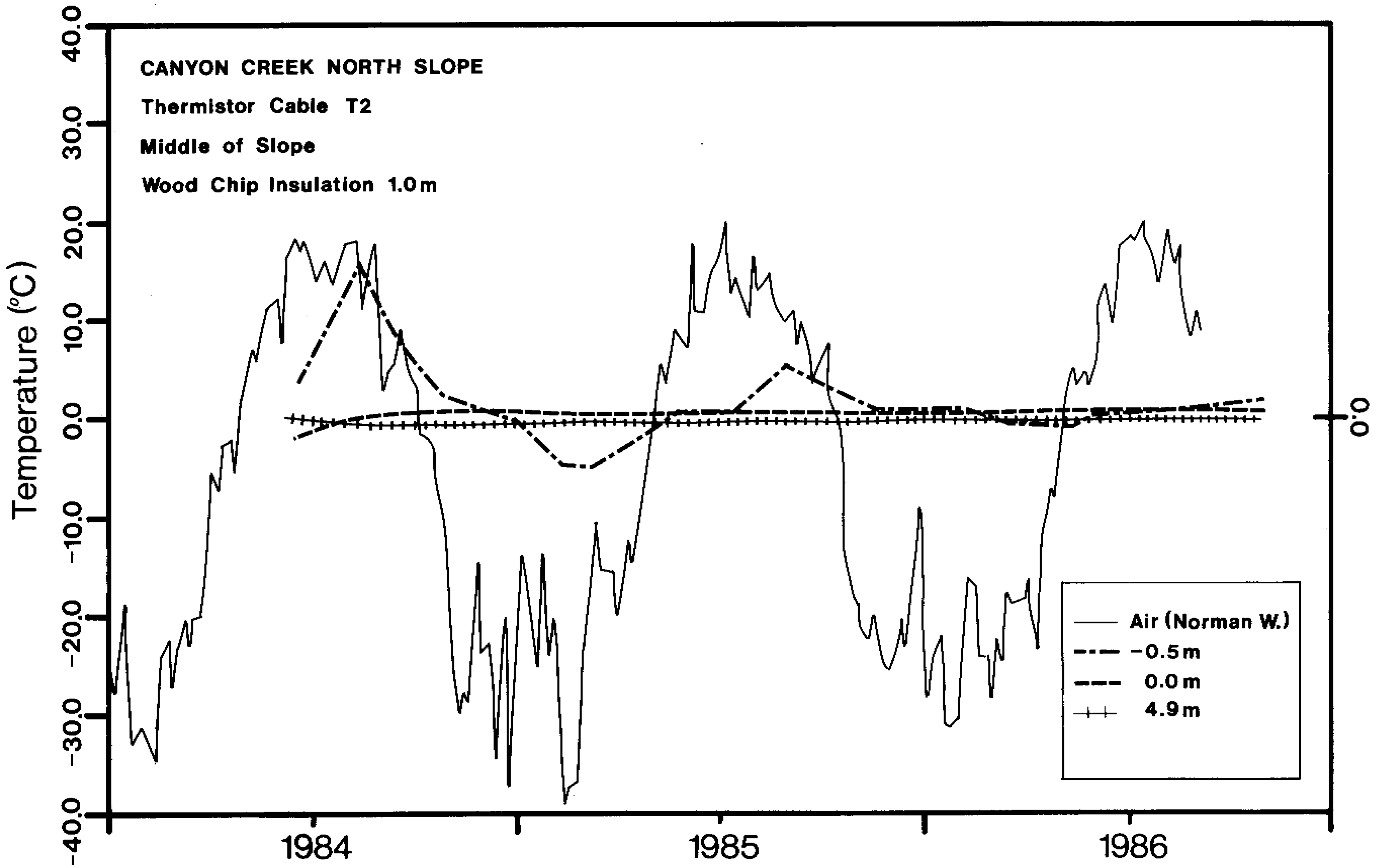


Figure 6-3. Canyon Creek North slope (84/2B) cable T2.

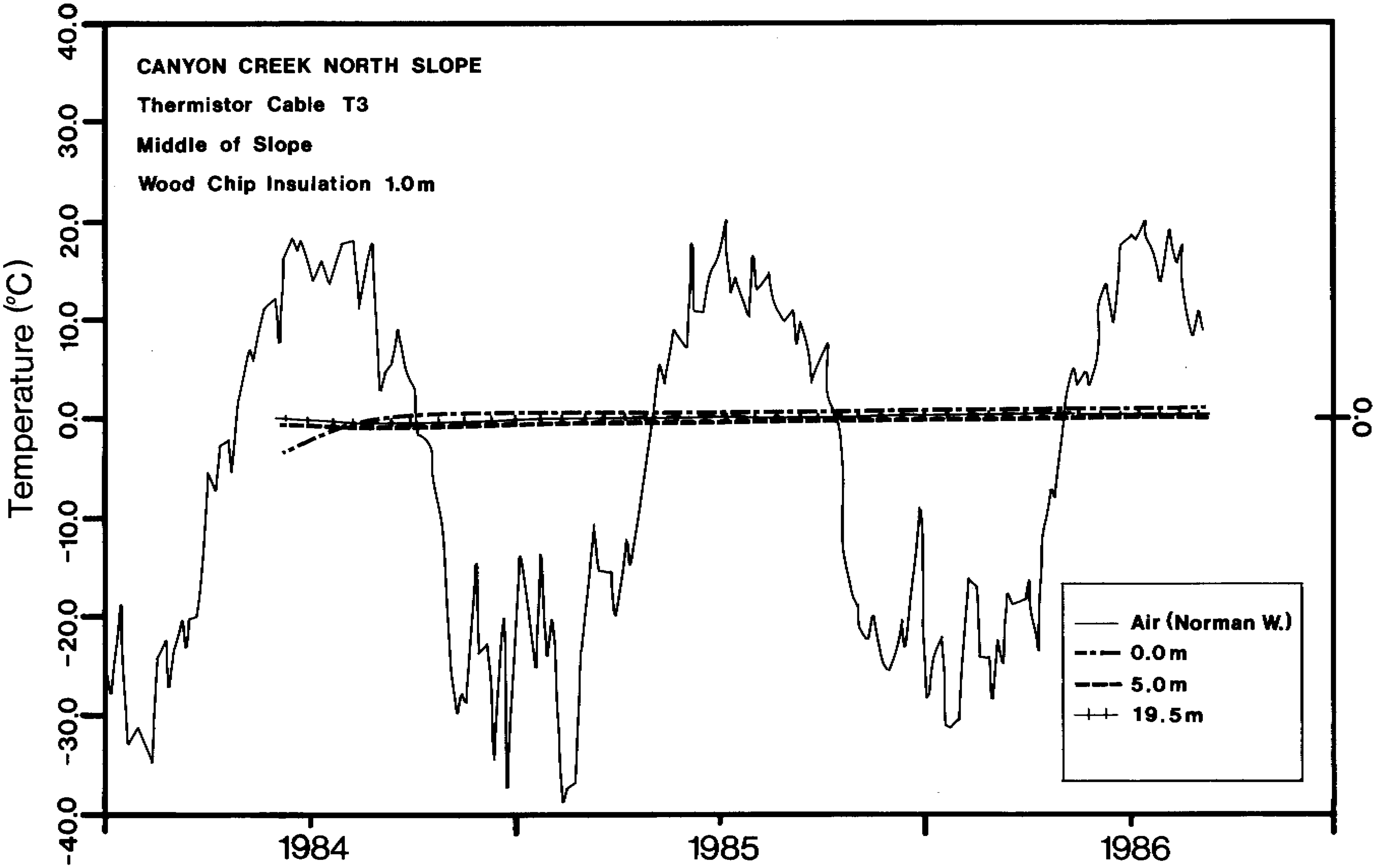


Figure 6-4. Canyon Creek North slope (84-2B) cable T3.

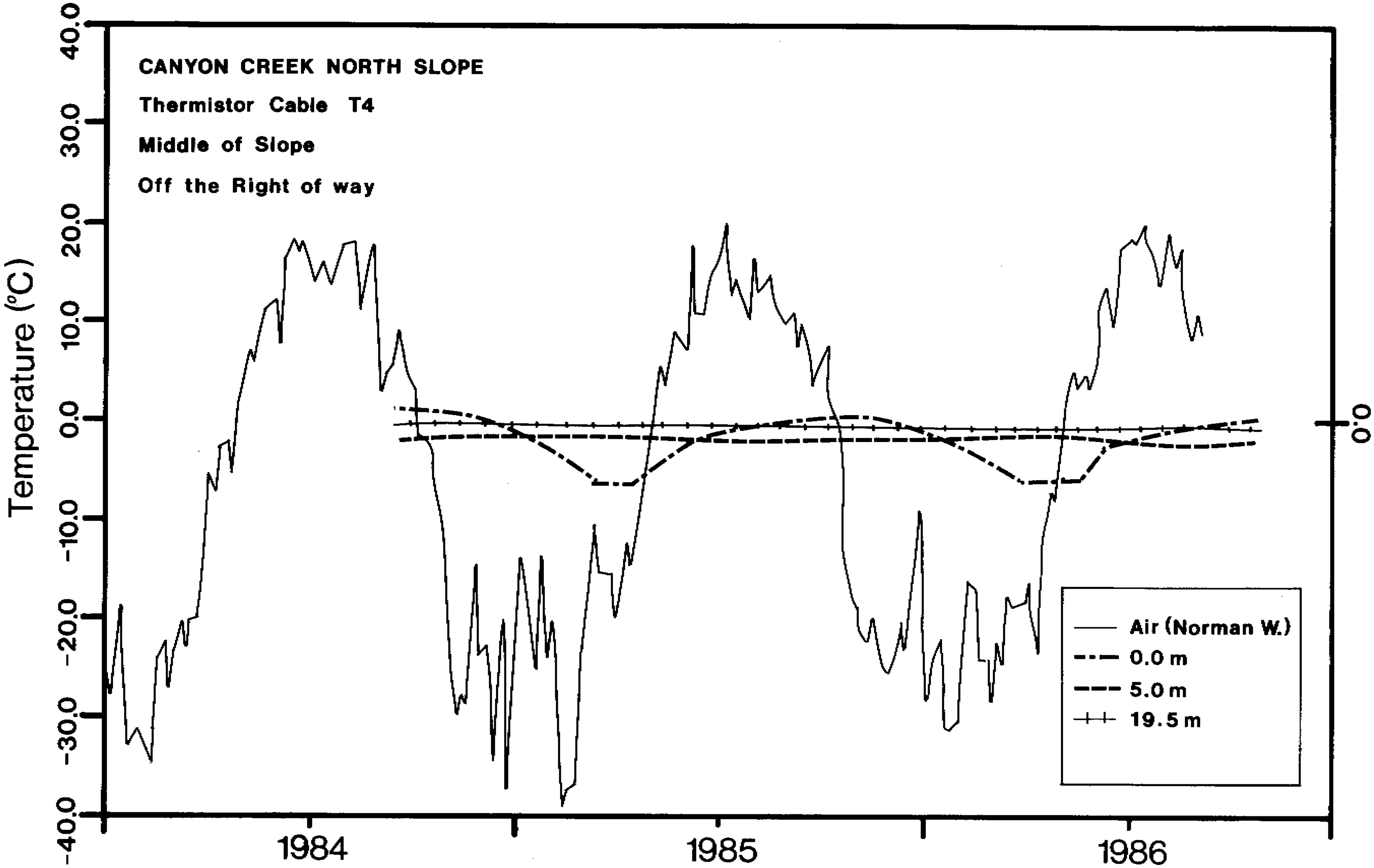


Figure 6-5. Canyon Creek North slope (84-2B) cable T4.

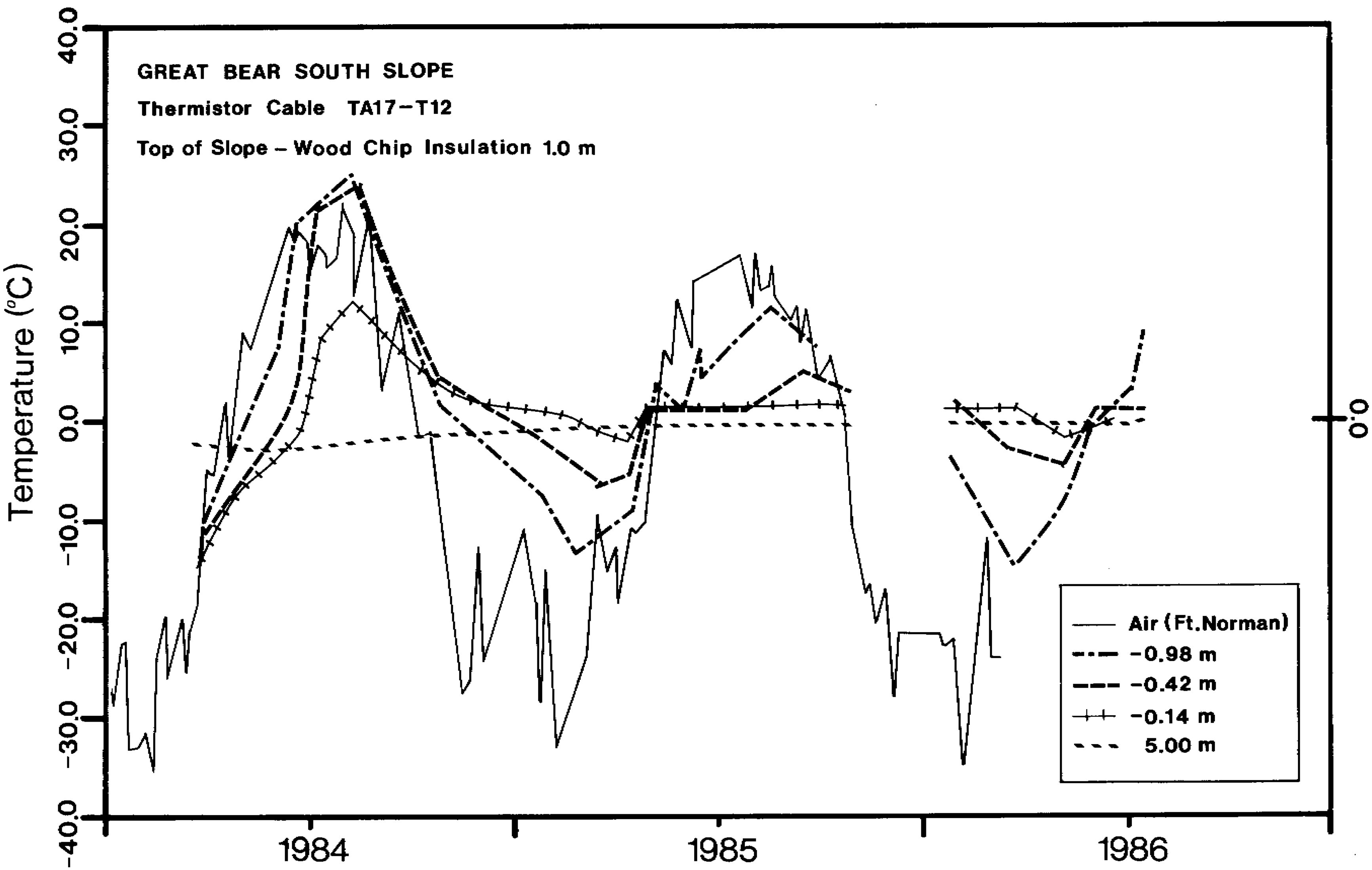


Figure 6-6. Great Bear South slope (#29) cables TA17 & T12.

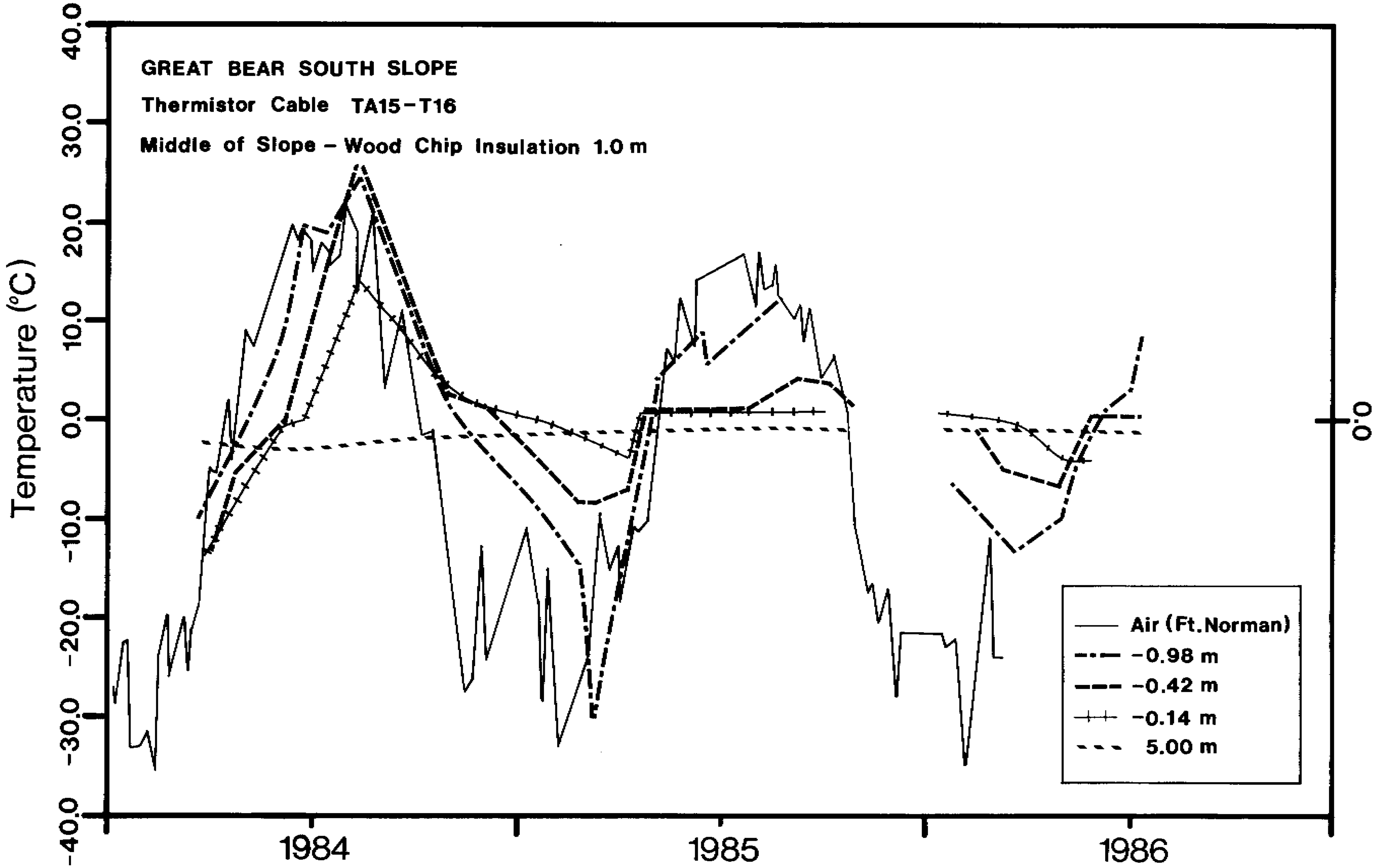


Figure 6-7. Great Bear South slope (#29) cables TA15 & T16.

are two cables in the wood chip cover. One is located near the top of the slope (Cable TA-17) and the other is located near the middle of the slope (Cable TA-15). At both of these sites, self-heating was most intense at the mid-height level of the insulation layer during the first summer period and was less evident during the second and third summer periods.

Data collected in the fall of 1986 at Canyon Creek indicated frozen wood chips in the lower 10 cm of the wood chip layer left over from the winter of 1985-1986. The mean annual ground temperature at the ground surface interface with the wood chips remained at about -0.2°C, for the two periods September 1, 1984 - August 31, 1985 and September 1, 1985 - August 31, 1986. Ground temperatures, at approximately 5 m depth below this ground surface interface, have shown a warming trend throughout the period. The off right-of-way temperature cable indicated a mean annual surface temperature of about -2.5°C. This would indicate that even though the base of the wood chips is frozen throughout the year, there will continue to be an increase in the mean annual ground temperature at depth until a new equilibrium is reached. The time to reach the new equilibrium will be dependent on the amount of ground ice present. IPL designers have predicted that the mean annual ground surface temperature will increase and the factor of safety will be correspondingly reduced. The critical period for slope stability would be between 5 and 7 years after placement (W. Slusarchuk, personal communication).

6.2 PERFORMANCE OF WOOD CHIPS PLACED IN MARCH 1985

In March 1985, the second set of slopes along the pipeline right-of-way were insulated with wood chips. Temperature data from one of these slopes (Mackenzie River South slope (slope 142) are presented in Figures 6-8 to 6-9 for the period March 1985 to June 1986. These data span one summer period and one winter period. Note that data gaps exist between early November 1985 to early March 1986. The slope is a "retard thaw" design type. The temperature profiles, through the wood chips and into the soil beneath, show a similar trend to that of the wood chips placed in 1984 except that the self-heating phenomenon was quite evident during the second summer thaw period as well. Temperatures measured at the top of the slope in Figure 6-8 (Cable TA-14) indicate that the heat generated during the first summer dissipated very slowly. Temperatures measured at the bottom of the slope in Figure 6-9 show the heat remained in the wood chip layer throughout the winter. This was attributed to an early fall (1985) snow accumulation insulating the hot wood chips from the cold winter air and trapping the heat in the wood chips (Figure 6-10). This is considered to be undesirable, as the IPL design considered the summer self-heating effect of wood chips to be balanced by winter freeze back.

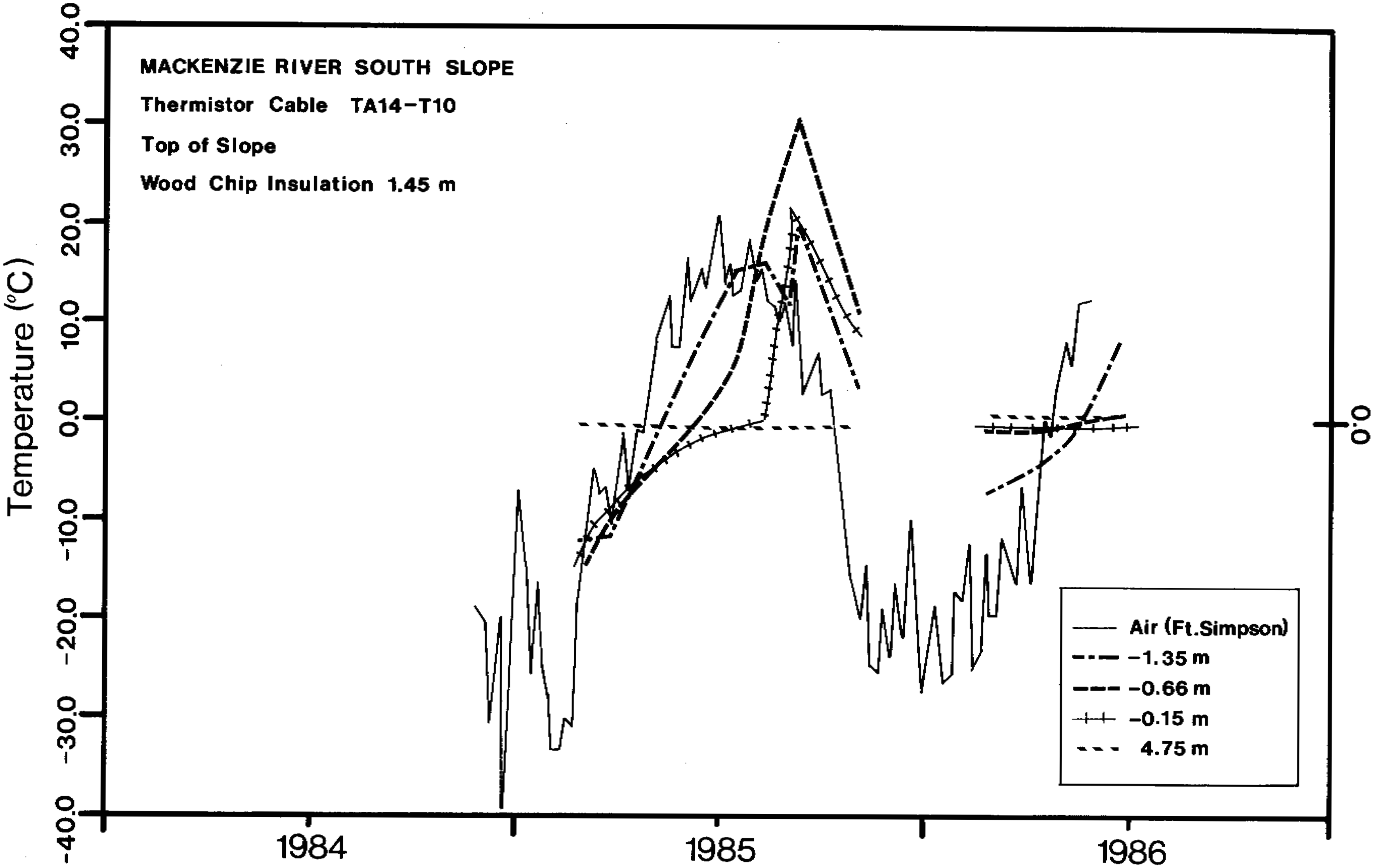


Figure 6-8. Mackenzie River south slope (#142) cables TA14 & T10.

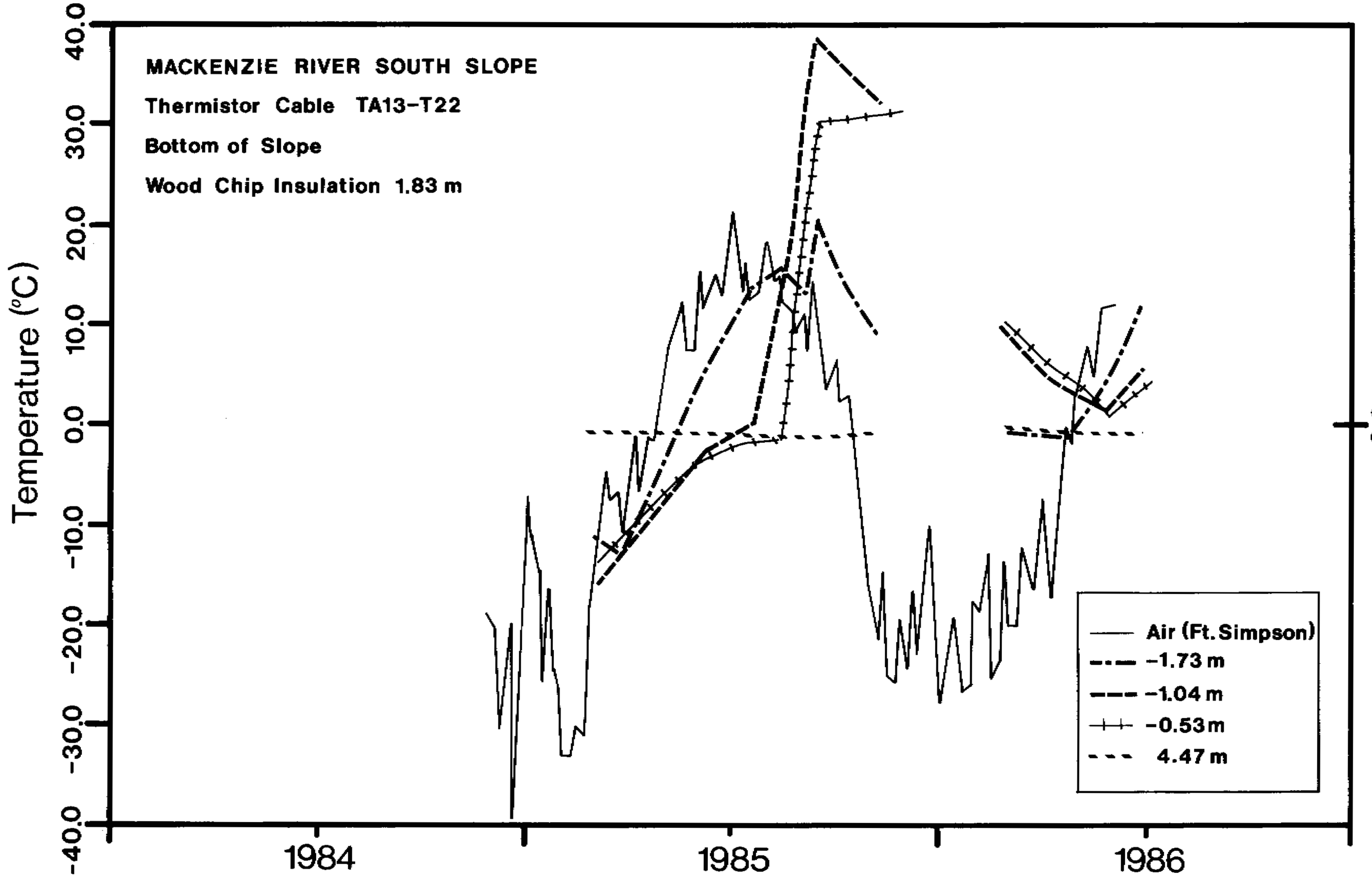


Figure 6-9. Mackenzie River South slope (#142) cables TA13 & T22.

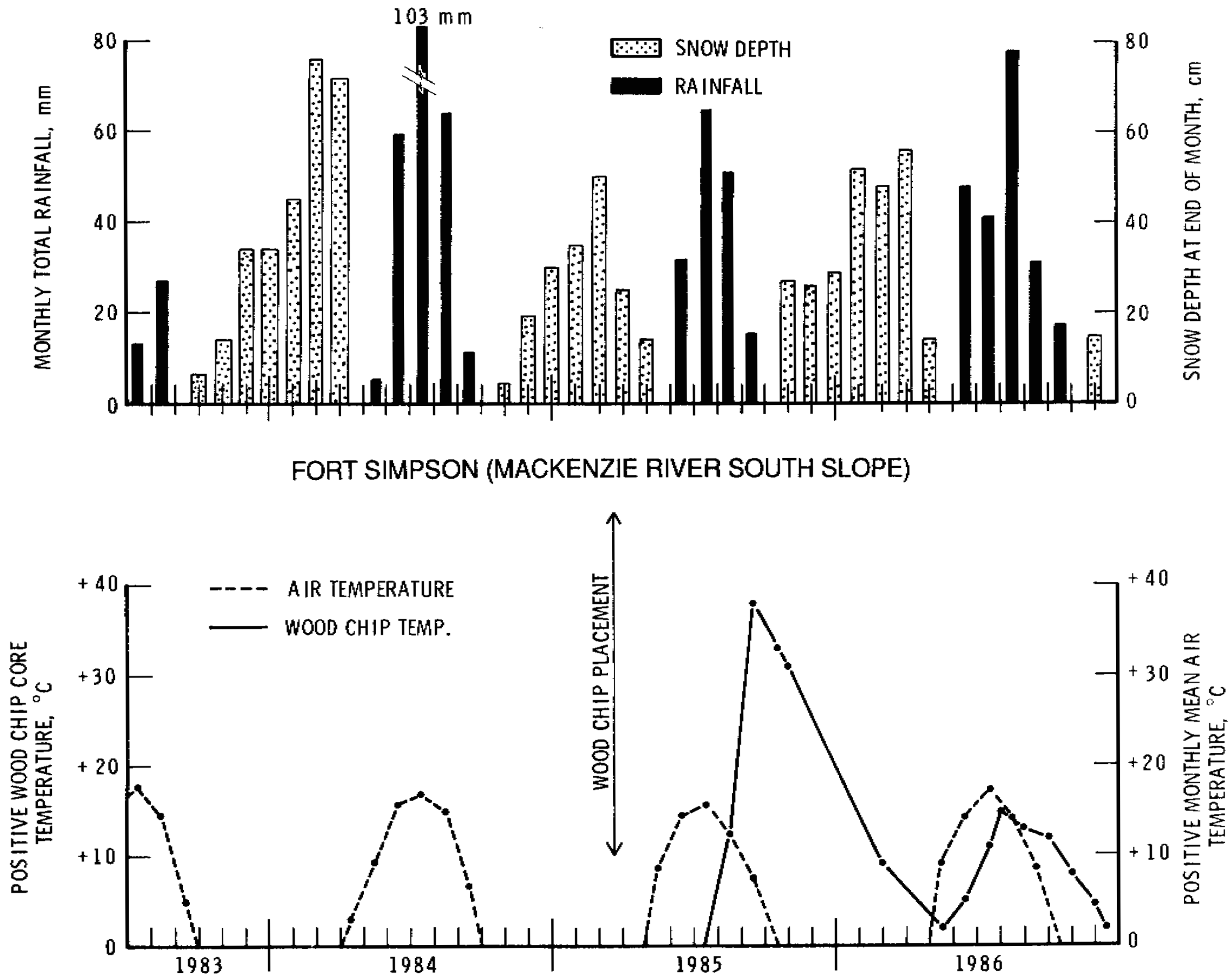


Figure 6-10. Wood chip temperatures on Mackenzie River South slope compared with air temperature and precipitation data from Fort Simpson Airport.

As a consequence of the monitoring program, IPL personnel removed snow from the Mackenzie River south slope in March 1986 to try and dissipate the heat build-up. Snow removal appeared to be effective in lowering the temperatures in the wood chip layer at the top of the slope, but at the bottom of the slope the warm temperatures decreased until late May/early June of 1986 and then began to increase again. In February 1987, IPL removed all the wood chips from this slope. Part of the wood chips were placed back on the slope about one month later in a thinner layer.

6.3 THAW DEPTHS BENEATH WOOD CHIP INSULATION - OBSERVED VERSUS PREDICTED

Figure 6-11 shows the predicted 25-year thaw depths beneath wood chip insulation of various thicknesses (McRoberts et al., 1985; Pick, 1987). Predictions were calculated using a one-dimensional model modified to account for internal heat generation in the wood chip layer. Two curves are shown in Figure 6-10; one for the situation with a 0.15 m surface peat layer and one where the natural surface organic layer has been removed. Both of these initial design curves were for a 13 m wide right-of-way. However, during the Norman Wells pipeline construction, most slopes were actually cleared to a width similar to the adjacent non-slope right-of-way (about 20 to 25 m). Calculations have also been made for a 20 m wide right-of-way with the surface peat removed. This other prediction accounting for a wider right-of-way was recently published by Hanna and McRoberts (1988), and reflects the width of the right-of-way effects on the depth of thaw.

Table 6-2 compares the predicted 25-year maximum thaw depths with the maximum measured thaw depths for the three slopes discussed above. The seasonal thaw depths for Canyon Creek and Great Bear have decreased with each successive year and moved up into the wood chip layer as indicated by the negative values. The thaw at measurement locations on the Mackenzie River slope has already exceeded the 25-year predicted thaw depth after about 1.25 years. IPL conducted vane shear tests in the thawed soil beneath the wood chips to determine the shear strength and hence the stability of the thawed soil layer. Reasons for the increase in ground temperatures under the wood chips will be presented in the following section.

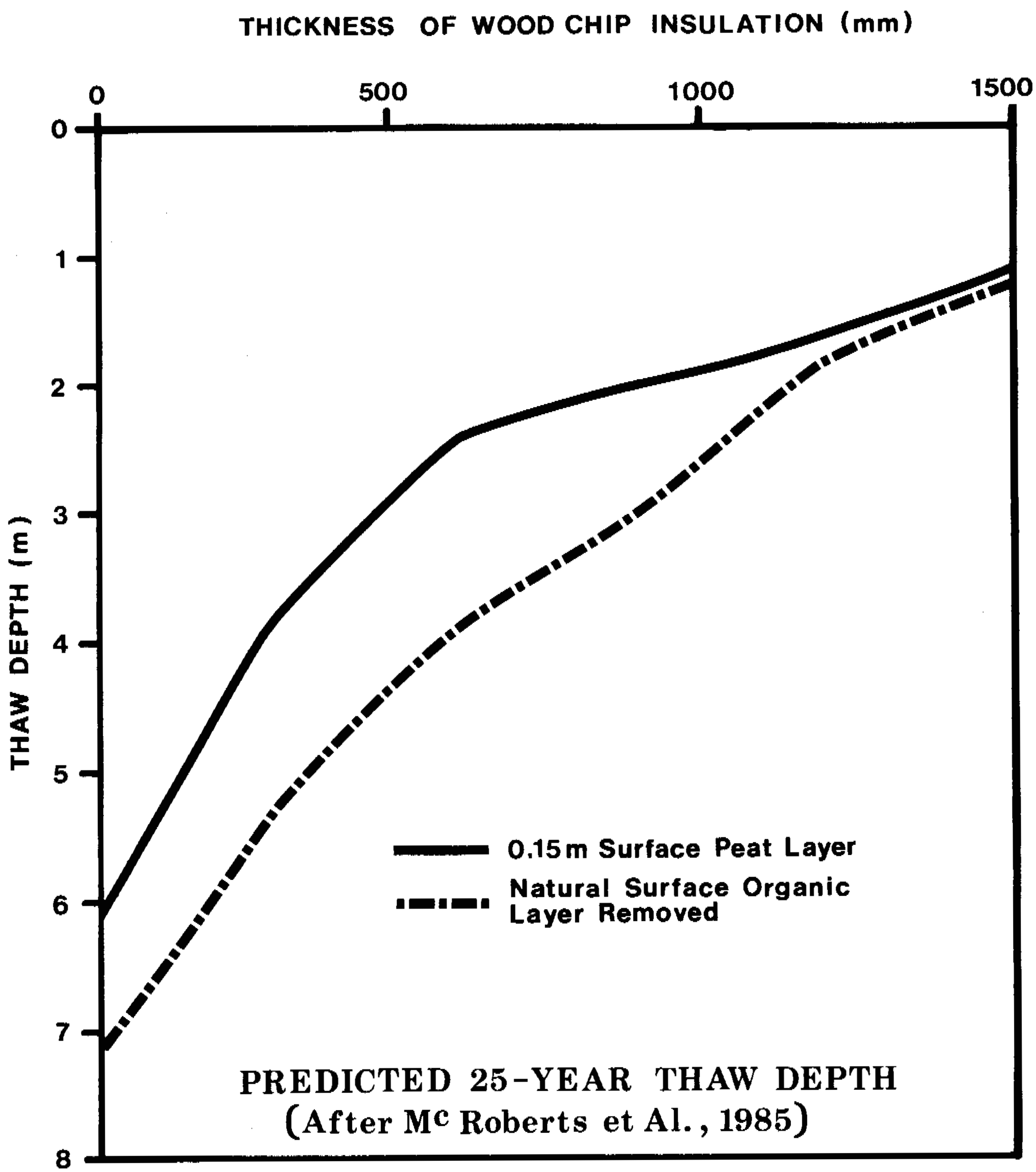


Figure 6-11. Thaw depth predictions as a function of wood chip thickness (after McRoberts et al., 1985).

TABLE 6-2. Thaw on three wood chip insulated slopes.

Slope Name	Wood Chip Thickness (m)	Predicted Thaw Depth After 25 Years (m)	Maximum Thaw Depth (m)		
			1984	1985	1986
Canyon Ck (km 19.3)	1.0	2.6	1.2	0.9	-1.0
Great Bear R. (km 79.3)	1.0	2.6	0.2	0.0	-0.3
Mackenzie R. (km 542)	1.45 -1.83	1.3	-	0.9	1.7

Note: Predicted thaw depths were taken from McRoberts et al. (1985). In Hanna and McRoberts (1988) it was shown that these predictions were for a 13 m right-of-way. This later paper presents a similar prediction for a 20 m wide right-of-way. All thaw depths are relative to the natural ground surface. Negative values refer to distances above the ground in the wood chip insulation.

6.4 INCREASE IN MEAN ANNUAL TEMPERATURES BENEATH WOOD CHIP INSULATION

For the most part, temperature measurements in the soil beneath the wood chip layers have shown a gradual increase since placement. This increase in mean annual temperatures is caused by a combination of the following conditions:

1. Thermal imbalance caused by excessive heat removal during the construction period due to removal of trees from the right-of-way and cold winter ground temperatures during trenching and pipe burial, prior to wood chip placement.

2. Summer heat generation due to biological degradation of the wood chips and early snow falls (September) preventing rapid heat removal into the air.

3. The influence of snowcover insulating the wood chips during the cold part of the winter. The net effect is to raise the mean annual ground temperatures by several degrees (Goodrich, 1982).

4. The presence of wet unfrozen wood chips (high latent heat), during the winter, combined with an insulating snowcover. Cooling of the underlying soil during the winter is restrained

by the high latent heat effect of the unfrozen wood layer. In conjunction with the reduced heat flow resulting from the overlying snowcover, the heat source (without any selfheating) provided by the underlying unfrozen wood chips is sufficient to maintain the wood chip-ground interface temperature above zero throughout the winter (Goodrich, 1978).

7. SUMMARY AND CONCLUSIONS

The following summary is based on observations and data obtained during construction and the first three to four years of pipeline operation. Some conclusions must be considered preliminary because of the short operational time of the pipeline and the variable time lag involved in detection of ground thermal and other changes, especially since the response of critical ice-rich permafrost terrain is slow.

In terms of overall pipeline and environmental performance in N.W.T. through 1988, 1) there have been no pipeline leaks or breaks and few pipeline exposures and 2) effects extending beyond the right-of-way have been localized and short term, primarily as a consequence of prompt IPL remedial action. Since the pipeline became operational, two pipeline water crossings have been rebuilt and the pipe has been reburied in one floodplain.

7.1 RESEARCH AND MONITORING PROCESS

The experience, observations and data bases available from the Permafrost and Terrain Research and Monitoring Program, established to address measures to protect the environment and safeguard pipe integrity, are unique: similar data bases on an operational pipeline are not publicly available for any other northern pipeline project in permafrost in North America or other circumpolar areas. The Program is also unique in being the first Canadian environmental monitoring program to address the issue of northern climate change in relation to environmental protection on a specific northern engineering project.

The goal of the Program, established in the IPL-INAC Environmental Agreement, is to "facilitate an evaluation of the impact management process in order to improve on impact evaluation and mitigation on the Norman Wells Piipeline and future projects". Improvements made in impact evaluation include:

(1) supplementing and refining parameters examined,
(2) testing and utilizing various automatic and manual data recording and handling systems and
(3) examining frequency and timing of monitoring measurements.

Data are used by government, industry and others to test criteria and models used in predicting terrain response to disturbance, to evaluate environmental mitigation on the Norman Wells pipeline, and to plan and review future projects.

Improvements made in mitigation as a consequence of discussions and review of observations and data from the Permafrost and Terrain Research and Monitoring Program and the Company's own monitoring program include:

(1) changes related to operating oil temperatures (additional instrumentation associated with pump stations, changes to pumping system, lowering oil temperature, rapid shutdown if oil is hot)
(2) review of data and initiation of remedial activity related to wood chip insulation of thaw sensitive slopes (e.g. wood chip thickness changes, snow removal, frequency and timing of data collection)
(3) review of rate of thaw settlement and use of surface changes to indicate when thaw settlement might be affecting conditions below the pipe (increased IPL geotechnical monitoring)
(4) more timely exchange of summer precipitation data from storm events in remote locations along the pipeline to facilitate prompt investigation and remedial work, where necessary, following storms (GNWT fire weather network).
(5) remedial measures implemented by IPL as a result of notification from observers on the Research and Monitoring program (e.g. pipe exposures, gullying and potential pipe exposure, flowing water in ditchline and at base of wood chip insulated slopes, tension cracks on slopes, stream bank erosion).

7.2 CLIMATE

Climatic and related hydrological conditions have played an important role in determining terrain response to disturbance during the period 1983-1988. The key climatic related parameters have proved to be air temperature, winter snowcover, spring runoff and precipitation.

Air temperature acts as a primary control on ground thermal regime; other factors being equal, it determines rate and depth of summer thaw, and duration of winter freezing. Winter air temperature and snowcover together control the window for winter construction and access for maintenance activities. In winter 1983-84, for example, below-normal snow depth contributed to problems of trafficability on northern sections of the ROW and on the Norman Wells to Fort Norman winter road. At several locations, thick snowcover on wood chip insulated slopes has reduced the winter release of heat generated by wood chip decomposition. This has necessitated remedial removal of snow.

Spring runoff and summer precipitation determine the volume of surface drainage, and the extent of surface erosion and flooding at stream crossings. This may also result in possible damage to drainage control structures. Precipitation intensity is a crucial factor; if the rainfall exceeds the infiltration capacity of the ground then overland flow occurs. This condition occurs most frequently in relation to summer storm events, which may affect only short segments of ROW at any given time. The frequency and spatial distribution of these events is hard to predict or even evaluate, given the small diameter of the storm area relative to the spacing between meteorological stations.

Climatic conditions in 1983-88 have shown considerable variability both from station to station and from year to year. For example, air temperatures and snow depth may be below normal in January at Norman Wells and above normal at Fort Simpson, and yet the situation may be the reverse in February of the same year. This underlines the problem of using mean monthly data to predict climatic conditions along the pipeline route.

There is some evidence of a systematic climatic warming trend at Norman Wells and Fort Simpson (AES/EMR work in progress, A.S. Judge personal communication). The magnitude of change observed (approximately +0.2 to +0.5 degree over the last 40 years, 1947-1987) is consistent with predictions based upon global circulation models. Over the same time period, there has been a marked decrease in depth of snow on the ground at Norman Wells at the end of January (Norman Wells A - AES station). Further data are required to fully evaluate these trends, however they suggest that the effects of climate change and variability should be taken into account when planning the design of future Beaufort pipelines, or the long-term maintenance of the Norman Wells Pipeline. Specifically, warmer temperatures and less snowcover may significantly reduce the window for winter vehicle access to the ROW and winter roads, and will have implications for geothermal models of pipeline-terrain interaction.

During the course of the pipeline research and monitoring program, several critical gaps in the climatic data base have been identified. These relate primarily to variability in winter snow depth and summer precipitation. Data collected by the PTRMP at instrumented sites have made a significant contribution to filling some of these gaps. In addition, climate data from other (non-AES) sources, particularly from seasonal Forestry stations have been used extensively. These provide an essential supplement to the AES data set, without which critical information regarding summer storm events and rainfall variability with elevation would not be available.

7.3 PIPE TEMPERATURES

Pipe temperature observations cover construction and two years of operation of the pipeline, when the oil flow was about 21,700 to 23,700 b/d and below design capacity of 30,000 b/d. They are based on monthly readings from thermistors (temperature sensors) strapped around the outside of the pipe at 23 thermal fences from km 0.02 to km 819.

The short term thermal behaviour of the Norman Wells pipeline is that of a warm line, i.e. mean annual temperatures >0°C, both through the widespread discontinuous permafrost terrain in the northern part of the route (north of Wrigley) and the sporadic discontinuous permafrost terrain in the south. Mean annual pipe temperatures recorded at the permafrost and terrain monitoring sites show a general trend of increase from north to south along the pipeline route. In general (75% of the thermal fences) mean annual pipe temperatures increased during the first two years of pipeline operation. The rate of pipe temperature warming was greatest in the first year of operation, partly as a result of cooling of the ground during construction. Although average oil flow per day also increased over this time period (from 21,700 to 23,700 b/d), average temperature of the chilled oil provided by ESSO to IPL decreased from -2 to -5°C.

Mean annual pipe temperatures recorded at thermal fences in the northern part of the route (km 19 to 272) ranged from +0.2 to +1.2°C after two years of operation. The only site with a mean annual pipe temperature below 0°C is 84-1 located 20 m downstream from the start of the pipeline at Norman Wells (chilled oil input). Mean annual pipe temperatures recorded at the southern fences, ranged from +1.8 and +4.8°C after two years of operation.

The generally warm mean annual pipe thermal regime indicates that frost heave due to a permanent frost bulb around the pipe is not of concern except near Pump Station 1. All thermal fences from Table Mountain (km 271) south to Petitot River South (km 819.5) have either 1) positive pipe temperatures throughout the winter months (i.e. permanent thaw bulb) or 2) pipe temperatures which remain at 0°C or a few tenths of a degree below throughout the winter, indicating complete freezeback around the pipe probably does not occur.

The permanent thaw bulb/lack of complete freezeback phenomena are in part attributed to 1) the generally wet conditions in the trench and hence the large amount of latent heat that must therefore be extracted in order for phase change to occur and temperatures to drop below freezing, and 2) for those sites within 30 km south of Pump Station 3 (sites 85-10 through to 85-12), the marked oil temperature increase on passage through a pump station (about 2 degrees). Recorded pipe temperatures at site 85-10, a few kilometres south of Pump Station 3 are above 2°C throughout the winter.

With the exception of these warm winter pipe temperatures recorded at monitoring sites within 20 km downstream from Pump Station 3, observed pipe temperatures (monthly, manual) have been within the range of predicted values.

7.4 PIPE - GROUND TEMPERATURE COMPARISONS

Pipe to ROW

Mean annual pipe temperatures are generally warmer (on average by 1.5 degrees) than mean annual ground temperatures on the ROW outside the ditch area at a depth similar to that of pipeline burial (i.e. sensor with nominal burial depth of 1 m). These latter mean annual ground temperatures ranged from -1.6 to +3.6°C for the second year of operation compared to a range of -0.2 to +4.8°C for mean annual pipe temperatures. The ground thermal regime adjacent to the pipe in the ditch is thus different from the ground thermal regime of the rest of the ROW, whether a site has been previously cleared or not.

The warmer pipe temperatures result in large part from the more disturbed conditions in the ditch as compared to the rest of the less disturbed cleared ROW. Ditchline subsidence, due initially to subsidence of backfill (which could not be easily placed during winter construction), was evident in mid 1986 on a third of the route based on interpretation of July 1986 air photos (Hardy, 1986). The ditch area is often subsided and frequently filled with water, providing a potential channel for water flow.

Recognizing that 1) for the pipe, the "surrounding soil" and "adjacent ground temperatures" are that of a disturbed trench within a cleared ROW and not those of "undisturbed" terrain off-ROW, 2) the pipe thermal regime follows an annual wave similar to that of the ground thermal regime (with the exception of site 84-1 where temperature is controlled at the source), and 3) mean annual pipe temperatures are within 3 to 5 degrees of mean annual ground temperatures on the ROW at a similar depth, then the pipeline may be described as an "ambient" line.

Instantaneous pipe temperature readings do however differ by more than 3-5 degrees from adjacent ground temperature readings. The pipe temperature is thus not solely controlled by the surrounding ground temperature. For many kilometres downstream from a pump station (perhaps more than 20 km), the operating conditions (oil flow rates, hence pumping pressures and oil temperatures) play a predominant role. Furthermore the pipe temperatures respond to average conditions over some distance and do not appear sensitive to changes in terrain less than 1 km in extent. Observations at sites with multiple thermal fences indicate that although differences in the terrain, ground thermal regime on ROW, snow conditions, aspect, and trench conditions occur from one fence to the next, the pipe temperatures change very little. The length scale required for the pipe to come into equilibrium with surrounding terrain is much greater than the scale of spatial variation in the ground thermal regime.

The pipe temperature instrumentation installed in the summer of 1987 at eleven fences will provide more frequent pipe temperature readings. These data will permit a more detailed study of the fluctuations in pipe temperature and their decay both in time and distance away from a pump station. An analysis of these data, coupled with additional and automated instrumentation in the ditch close to the pipe, will also allow an examination of the decay of fluctuations away from the pipe (outwards as opposed to along) and should help to better understand the pipe thermal regime and the dominant heat transfer processes with the surrounding soil.

On-ROW to off-ROW

The ground temperatures on the ROW (nominal depth of 1 m) also showed a general warming trend. This trend was observed at 65% of the fences. By contrast an unambiguous warming was noted at only about 25% of the off-ROW sites (1 m sensor). The warming trend on the ROW is likely principally a result of pipeline construction and operation rather than a response to the increase in mean annual air temperatures observed at Norman Wells and Fort Simpson. Increases in mean annual ground temperature of up to 1 degree have been recorded on the ROW to depths of up to 10 m. The ROW ground thermal regime has not reached equilibrium following construction. The thermal response of ice-rich soils and frozen thick organic terrain is particularly slow due to latent heat effects (additional heat required for phase change).

Mean annual on-ROW temperatures at 1 m are generally warmer than those off-ROW, by 1 degree on average. Mean annual ground temperatures off-ROW ranged from -2.8 to 2.5°C after two years of operation, compared to a range of -0.2°C to +4.8°C for mean annual pipe temperatures.

7.5 ACTIVE LAYERS AND THAW DEPTHS

The active layers on the ROW at the end of the 1987 thaw season ranged from <0.5 to <3.0 m, as defined by the maximum depth of penetration of the 0°C isotherm and measured by the ground temperature cables. The active layers off-ROW by comparison were generally <1 m. Active layers on-ROW increased (by up to 1 m) through to the end of the 1987 thaw season, while off-ROW they generally stayed the same. The active layers on-ROW continue to increase in thickness.

Thaw depths beneath the pipe, as derived from IPL geothermal simulations to predict maximum thaw depths after 30 years of operation, should vary from 2 to 4 m after 2.5 years of operation. Observed active layer thicknesses on-ROW to the end of 1987 fall within these predictions at all but one thermal fence. Continued monitoring of the ground thermal regime will be necessary to determine if the active layer remains within the 30 year design thaw depth prediction (which varied from 6.1 to 12.2 m depending on terrain type and pipeline segment). This will be particularly of interest at those sites where the surface organic layer was bladed across the full ROW and the remaining thickness was less (i.e. <30 cm) than that used in the geothermal simulations to determine maximum thaw depths.

7.6 SURFACE SETTLEMENT

Variable amounts of surface settlement have occurred on the right-of-way since clearing and pipeline construction. This settlement is due primarily, outside trench, to thaw subsidence of ice-bearing sediments. In the trench area the maximum recorded settlement to the end of the 1987 thaw season had reached 50 cm or more at 13 of the 23 thermal fences, with 3 fences showing a maximum of 100 cm or more. Some of this settlement was initially a result of the subsidence of the trench backfill which was placed as a frozen and uncompacted berm over the pipe during winter construction. For the ROW area outside the trench, maximum recorded settlements of 50 cm or more have been observed at 6 permafrost fences. These settlements are all minimum values in that any settlement that might have occurred during the first summer following pipeline ROW clearance or widening has not been documented, the sites having only been established at time of pipe laying which usually occurred one year after ROW clearance.

A few ice-rich sites, notably 84-1 (km 0.02) and 84-3A (km 79.2), where the originally hummocky terrain was levelled on the ROW and much of the surface organic layer removed during construction, have again developed a conspicuous hummocky relief (over 50 cm). Right-of-way surface settlement is ongoing, both in the trench and on the remainder of the ROW, and the rate of settlement has been variable from year to year and site to site. As thaw depths progress beneath the pipe, it may then be possible to infer settlement of the soil beneath the pipe based on observed increases in surface settlement.

A comparison of recorded surface settlement with thermal erosion susceptibility predictions (i.e. predictions of mean surface settlement, see section 4.4) shows that in the trench area maximum surface settlement in excess of the predicted values has been recorded at 9 permafrost fences (1, 3A, 7A/B/C, 8B/C, 10B, 12B). In general, the predicted values are exceeded in localized pockets representing a small percentage of the terrain surveyed. For the rest of the ROW localized areas of surface settlement in excess of the predictions have been observed at 4 fences (1, 3A, 8B, 8C).

Analysis of the cores retrieved from boreholes at the thermal fences indicates that the rate and amount of settlement will continue to be variable in response to both the heterogeneity in ground ice distribution and in rates of thaw. Excess ice has been observed for example at depths >5 m at sites 85-7B and 85-8A (Patterson and Riseborough, 1988).

7.7 WOOD CHIP INSULATION

The following is based on a review of IPL and government data from 15 instrumented slopes through fall 1987. Wood chips have exhibited self-heating during the first summer period after placement on the slopes. Except for about six slopes the warm temperatures built up in the wood chip layers were dissipated with the coming of the cold fall air temperatures. Early snow cover provided an insulating layer which may have prevented heat removal from the other slopes. Some reheating occurred in most wood chip layers during the second summer period, but usually to a lesser extent. IPL has followed up on the self-heating phenomenon and has observed snow melt patterns that indicate hot spots in the wood chip layers of a few slopes. Persistent heating on a few slopes has prompted IPL to try some remedial measures including:

- spraying water on some slopes in the fall of 1986,
- removing snow from two slopes during March 1986,
- removing and replacing wood chips from three slopes during the winter January - March 1987,
- installing vent pipes to allow cold air circulation in one slope in the fall of 1987.

The internal heating on some wood chip covered slopes, where thermistor cables were installed, has caused thaw in excess of the 25-year predicted thaw value. The evidence from snow melt patterns suggest that internal heating occurs in pockets within the wood chip layer and is not extensive on any one slope. IPL has tried several mitigative methods to cool down localized hot spots on a few slopes.

The high latent heat effect of the wet wood chip layer was considered to be an advantage in the thermal design, to reduce the influence of the warm summer air temperatures. This was probably not considered to be a problem during the winter, as the wood chips were thought to freeze back. From the monitoring data, this was often not the case, due to a thick insulating snow cover.

Snow accumulation on the wood chip insulation, along with the conditions mentioned above, have combined to cause an increase in the mean annual ground temperature. This appears to be gradually thawing the soil beneath the wood chip layer. The influence of this thaw is more extensive throughout the wood chip covered slope surface than the self-heating phenomenon. Whether this will cause future slope instability remains to be seen. This is a major reason for continuing the slope monitoring program. IPL designers have indicated that they have considered this and have modelled an increasing mean annual ground temperature. This aspect of the design has not been presented or discussed in any of the three published papers on the wood chip insulation design approach. This aspect of the performance of wood chips may adversely effect the long term insulating capability.

7.8 TERRAIN PERFORMANCE

During construction, terrain disturbance resulted from grading of the ROW surface, reduction of slopes to design angle, and excavation and backfill of the pipe ditch. Although work was carried out from a snow covered and/or frozen surface, in some areas the ROW was bladed down to mineral soil. This resulted in partial or complete loss of the surface organic soil and vegetation layer. Deep grading of this kind occurred under two main circumstances: (a) As a result of the lack of snow cover during the early part of the 1983-84 construction season, particularly between Norman Wells and Fort Norman; (b) Levelling of hummocky terrain to increase trafficability and permit safe operation of equipment. This situation occurred frequently south of Fort Simpson, where the ROW crosses areas of peat plateaus with steep flanking slopes. The effects of organic layer disturbance in terms of enhanced thaw settlement and delayed revegetation have not yet been determined.

The most pronounced effect of terrain disturbance during construction has been the widespread subsidence of material along the ditchline. This commenced during the first thaw season following construction and resulted in the ponding of and channelling of water along the ROW. Subsidence probably occurred as a result of the use of ice or snow-rich backfill, or thaw consolidation of frozen, blocky backfill. A survey carried out by IPL, based upon interpretation of air photgraphs taken in July 1986, indicated that approximately 30% of the ditch was visibly subsided at that time. Ditch subsidence has presented a persistent maintenance problem. For example, 80 km of sunken ditch (greater than 20 cm below grade) was backfilled in winter 1985-86 and 1986-87, using about 100,000 m^3 of material.

Thaw settlement of ice-rich terrain is also occurring as a result of the growing thaw bulb across the entire ROW. At PTRMP instrumented sites, topographic surveys indicate a cumulative settlement to date of up to 1 m. It is too early to predict the effect of this more general surface subsidence on ROW drainage conditions. However, it will be necessary to constantly monitor drainage control structures to ensure that they respond to changing topography. There will be an increasing tendency for cross drainage to become channelled along the ROW, which will be at a lower level than surrounding terrain.

In most cases erosion structures have performed well in limiting surface erosion of the ROW. However, numerous examples of small-scale erosion (gullying less than 10 cm deep) have occurred, frequently triggered by intense summer precipitation events. More serious erosion in these cases has frequently been prevented by prompt IPL maintenance activities, resulting from reports by line patrols (weekly or more frequent). A smaller number of erosion events have resulted in gullying to depths of more than 20 cm, with associated loss of ditch backfill and, in several instances, exposure of the pipe. Such erosion occurred in 1984 at km 67, on the south flank of the Norman Range, and at km 78, on the north side of the Great Bear River. In 1985, erosion affected the wood chip-insulated slope at km 225, on the north side of Blackwater River, and washouts occurred at several locations south of Fort Simpson. In 1988, a deep gully was eroded by cross drainage across the ROW at km 323. In each case, remedial repairs were carried out by IPL to restore the ROW and upgrade drainage control structures.

ROW erosion has generally resulted from the complete or partial failure of drainage control structures to adequately control runoff. This has occurred either because of their misalignment during construction or subsequent irregular subsidence, particularly in the ditch area. Erosion has also occurred in areas where no control structures were included in the original design. For example, in 1985 ditch erosion occurred on the south side of the Redknife Hills (km 610-700), along segments of the ROW characterized by long, gentle slopes. The effect of permafrost conditions on the frequency and magnitude of ROW erosion is not clear. Certainly, ice-rich permafrost is subject to thermal as well as mechanical erosion. Erosion events resulting from ditch or ROW settlement may also be linked indirectly to permafrost conditions. In spring, surface runoff and erosion potential may be increased due to the presence of impermeable frozen ground. However, in most cases surface erosion does not appear to have been significantly influenced by permafrost occurrence.

ROW erosion, and associated disturbance of mitigation structures, has occurred at several stream crossings due to high water events and, in some cases, insufficient streambank protection. At a few localities, it appears likely that water levels were further raised as a result of ice dam or icing formation. In 1984, the south side of the Seagram Creek crossing was undermined, resulting in collapse of the slope toe. The slope had not been protected by rip-rap as specified in the design. In 1986, cribbing and wood chips were lost from the north bank of a small stream crossing at km 133 during a spring flood event.

Two major flood events have affected the Hodgson Creek crossing (km 305), in June 1986 and July 1988. In both cases, rainfall recorded at the nearby Mount Gaudet Forestry station reached or exceeded the estimated 100-year maximum 24-hour precipitation value. The 1986 flood resulted in a major shift in the main river channel, causing water flow along the ROW and threatening erosion of the north sag point. Remedial action consisted of deep burial of the pipe on the south side of the flood plain, and construction of a river training structure on the north side to protect the sag point. During the 1988 flood, the training structure was partially destroyed. High flood levels also affected the Ochre River crossing in July 1988, causing rapid river bank erosion and exposure of the pipe.

The geomorphic stability of uninsulated slopes has been assessed solely by observations of sediment mass movement and other indicators of incipient instability. Mass movement features were observed on several side slopes during the spring following construction (e.g. km 65, 273). Mass movement of material on stream crossing approach slopes occurred in 1984 at Kakisa River (km 732), in 1985 at Jean Marie Creek (km 577) and in 1986 at Ochre River (km 286). Tension cracks, observed in wood chip insulation at Bosworth Creek, Great Bear River and Ochre River, provide possible indications of sediment movement on the underlying ground surface. No major slope failures have occurred to date (October 1988).

8. RECOMMENDATIONS

The following recommendations are based on observations and results from the Permafrost and Terrain Research and Monitoring (PTRM) Program on the Norman Wells pipeline. They cover pipeline construction (1984, 1985) and the first three to four thaw seasons of pipeline operation in the discontinuous permafrost zone, northern Canada. The majority of the recommendations involve impact mitigation, improvements related to project planning, operations and maintenance, and environmental performance evaluation. Numerous recommendations emphasize the need for longer term data collection, especially to evaluate mitigation in ice-rich permafrost and the potential effects of climate change. From both northern engineering and environmental perspectives recommendations to future projects will be of even greater value when based on longer term results (Boreal Ecology, 1989b).

8.1 RESEARCH AND MONITORING PROCESS

Key issues:

- limited experience on pipeline projects and pipeline related environmental protection in permafrost terrain for both industry and regulators
- evaluation of environmental concerns
- anticipated/predicted and actual impacts
- improvements in impact evaluation and mitigation on Norman Wells Pipeline and future projects
- optimizing environmentally-safe cost-effective approaches
- "Environmental Agreement" - formal industry and government cooperation and evaluation

The Norman Wells to Zama Pipeline is the first oil pipeline completely buried in the discontinuous permafrost zone in Canada. It is viewed as a "pilot project" from which important lessons can be learned. Co-operative research and monitoring was established under the terms of a special "Environmental Agreement" signed between the federal government Department of Indian and Northern Affairs (INAC) and Interprovincial Pipe Line (NW) Ltd.

1. It is recommended that INAC continue permafrost and terrain research and monitoring until conditions stabilize (e.g. little evidence of erosion and settlement, or slope streambank and thermal instability), or until it is felt that no further practical lessons leading to improvements on the Norman Wells Pipeline or future projects are likely to be learned. In order to complete an annual performance evaluation under the

Environmental Agreement, government monitoring and/or surveillance is required throughout the life of the agreement.

2. It is recommended that government and industry implement cooperative research and monitoring programs on other northern projects in permafrost terrain, where evaluation might lead to improvements in mitigation, and improve on the capability to anticipate environmental problems. These include problems which might arise from effects of climate warming on thaw sensitive slopes, differential thaw settlement, frost heave and erosion potential.

3. It is recommended that future research and monitoring activities and funding be formalized through a similar signed agreement. Activities should involve government and industry co-operation and regular review of results and should be established in such a manner as to have long term continuity beyond the period of project construction.

8.2 REGIONAL ENVIRONMENTAL FRAMEWORK

Key issues:
- engineering design and pipeline mode (buried, elevated)
- route selection
- environmental protection.

A knowledge of the regional environmental framework, particularly climate, permafrost and terrain conditions, is essential to design cost-effective pipelines, determine routes, and plan for environmental protection. For the Norman Wells Pipeline, the wide spacing of meteorological stations and low level of baseline hydrological data have reduced the accuracy of runoff prediction models. The present program has contributed substantially to knowledge of geological and geothermal conditions along the Norman Wells Pipeline route. However, considerable gaps in information exist along the transportation corridor north from Norman Wells to the Beaufort Sea coast, particularly in regard to knowledge of meteorological, permafrost and ground ice conditions. The following recommendations are made in regard to these concerns:

A. Climate:

4. The AES (Atmospheric Environment Service, Environment Canada) climate data network should be upgraded along existing and potential northern transportation corridors, between the Beaufort Sea and the Provinces. There are specific data gaps relating to (a) regional climate and (b) local to meso-scale

meteorology (e.g. frequency and magnitude of summer precipitation events).

5. Climate data from other sources (including data collected at PTRM sites and AES/EMR automatic permafrost climate stations) should be integrated with the AES data base to increase the number of and decrease the spacing between recording stations. Seasonal data (e.g. from GNWT Forestry stations) are also of value, particularly in monitoring the distribution, frequency and magnitude of summer precipitation.

6. Future pipeline proponents should consider the telemetry of meteorological data (especially temperature and precipitation values) from pipeline remote valves and pump stations. If future pipelines are designed according to a less conservative, "monitor and maintain" philosophy, then the collection of real-time data is strongly recommended. It would allow for the rapid mobilization of maintenance crews in response to precipitation events liable to cause ROW erosion. This mode of data collection would also make a significant contribution to the climatological data base in areas which are not adequately covered by the existing recording network.

B. Climate change:

7. To assist in both the planning and safe operation of future pipelines and the continued maintenance of the Norman Wells pipeline, increased attention should be focused upon the implications of climate change. Emphasis should be placed upon analysis of climatic trends and variability, as well as on mean conditions. Climatic change may limit the validity of using 30-year normals as inputs in geotechnical and geothermal models and environmental protection plans.

8. Pipeline proponents should examine current projected climate change scenarios and determine the sensitivity of their design and operation to potential climate change. A range of climatic conditions should be used, for example, in geothermal models, erosion control planning and design of water crossings.

9. During the course of geothermal/geotechnical assessment of pipeline route characteristics, the proponent should demonstrate knowledge not only of ground ice and soil type/texture but also of ground temperature and geothermal regime. Areas of warm, ice-rich permafrost and saline permafrost are of particular concern since they may be affected by increased creep, thaw settlement and slope instability during climatic warming.

C. Permafrost and terrain:

10. It is recommended that both government and industry continue to extend publicly available knowledge of permafrost terrain conditions along potential northern pipeline corridors. There is a particular need for additional information on ground ice content and distribution, and geothermal conditions. These baseline data are required for planning and environmental assessment and protection purposes, in order to evaluate potential thaw settlement, frost heave and determine preferred mode of pipeline construction (buried, elevated, insulated). They also provide control data against which to evaluate the actual environmental impacts of pipeline construction and operation.

11. On future pipeline projects, as on the Norman Wells Pipeline, every effort should be made to maximize the information derived from geotechnical boreholes and surveys, geophysical and geothermal investigations. This can best be achieved through co-operative industry/government research programs, and the establishment of a geotechnical data base.

8.3 THERMAL REGIME

Key issues:
- design concepts and construction in permafrost terrain
- thermal performance evaluation
- frost heave and thaw settlement mitigation
- stability of thaw sensitive slopes
- amount or extent of surface disturbance

The pipe and ground thermal regimes are key components of the pipeline thermal design and central to the evaluation of thaw settlement and frost heave designs and mitigation. The instrumentation installed at the PTRM sites has provided the main means of documenting the thermal behaviour of the pipe, as discussed in this report, and the ground thermal response to current climate conditions, and pipeline construction, operation and mitigation.

On the Norman Wells Pipeline to date (1984-1987), the pipe and ground thermal conditions have not stabilized in response to construction and operation. Until such time, thaw depths beneath the pipe and right-of-way will continue to increase, and permafrost degradation and thaw settlement will continue to occur particularly at sites with high ice contents.

12. It is recommended that thermal instrumentation form an integral part of the monitoring and thermal evaluation of future pipeline projects in permafrost terrain.

13. It is recommended that the present pipe temperature and ground temperature monitoring program be continued in order to annually review and evaluate the thermal regime and mitigation of the Norman Wells Pipeline, and to improve design and evaluation of future pipelines in permafrost terrain. It is premature after this short observation period, and under the currently "dynamic" thermal regime, to evaluate whether the Norman Wells Pipeline project has been designed and executed with sufficiently low energy input to assure that differential thaw settlement will be limited to an acceptable level over its 30 year life.

    At sites without data loggers, where manual measurements are required, the recommended frequency for the continued thermal data collection (for examining depths > 1 m) is every 6 weeks in summer, and every 8 weeks in winter, until conditions on-ROW are in thermal equilibrium with the surrounding terrain. Thereafter manual data collection should continue at a lower level of every 2 to 3 months as appropriate and at selected sites, for the life of the pipeline. This continued monitoring will also document the thermal response of the ROW and surrounding terrain to climate change.

14. It is recommended that observations address the following data gaps and questions identified during the first 5 years of the program:

    i. the pipe-ground heat exchange is complex, therefore there is a need to better understand the thermal regime of the ditch and the mechanisms of pipe-ground heat exchange; conduction may not be the only mechanism of heat transfer away from the pipe, particularly in wet trench conditions, where water movement and hence convective transfer may occur.
    ii. the sensitivity of the pipe thermal regime to changes in oil flow (temperature and pressure).
    iii. the effects of changes in the pipe thermal regime on the thermal performance, and hence stability, of insulated thaw sensitive slopes (where ground temperatures are only slightly below 0°C).
    iv. the long term trend in mean annual pipe temperatures (currently above 0°C and increasing over this observation period)

15. It is recommended that long term observations of the thermal regime off right-of-way continue as these contribute to the study of the response and sensitivity of discontinuous

permafrost terrain to climate change. This knowledge is necessary to determine the combined terrain effects of climate change and changes due to pipeline activities.

8.4 THAW DEPTHS

Key issues:
- thaw settlement design and mitigation
- surface and subsurface geomorphic processes and hydrology
- stability of thaw sensitive slopes

Thaw depths beneath the right-of-way on the Norman Wells Pipeline have not stabilized and have not reached the maximum predicted design values (30-year predictions).

16. It is recommended that thaw depths continue to be determined in order to evaluate the thaw settlement design and mitigation.

17. It is recommended that development of methods, such as ground probing radar, for remote sensing the depth of thaw be continued to provide continuous profiles across the right-of-way and beneath wood chip slopes and to help understand differential thaw bulb development beneath the pipe and across the right-of-way. Standard physical methods for hand probing to the frost table are limited to depths of about 2 m.

18. It is recommended that the freezing characteristics of soils be considered in thermal performance evaluation of the Norman Wells Pipeline and in geothermal design and assessment of future northern pipelines in permafrost terrain. This could result in substantially different thaw depth predictions and observations particularly when thermal gradients are low. Although ground temperature measurements may be used to interpolate depths of thaw, the use of the 0°C isotherm (active layer) as the thermal boundary delineating the depth of thaw may not always be appropriate, particularly for soils with a freezing point depression. A knowledge of the freezing characteristics of soils is important to the proper interpretation of the depth of the phase change "unfrozen/frozen" (liquid/solid water) interface. It is this boundary which is relevant to thaw settlement predictions.

8.5 SURFACE SETTLEMENT

Key issues:
- use as an indicator of possible pipe settlement - effects on surface drainage, ponding and erosion
- select backfill requirements

Surface thaw settlement both in the trench and on the remainder of the right-of-way continues to occur at variable rates.

19. It is recommended that monitoring of surface settlement continue (via successive level surveys every 2-3 years), particularly at locations of high ice contents and at terrain transitions where differential thaw settlement may occur. These measurements will allow the determination of (1) thaw settlement of the right-of-way relative to the terrain off the right-of-way (important for surface drainage and erosion) and (2) differential thaw settlement beneath the pipe (important for pipe differential settlement).

    The recommended frequency for surface level surveys on future projects, where thaw settlement is of concern, is as follows: 1) as soon as possible after site establishment (generally immediately after construction) to obtain a baseline; measurements after clearing and before construction would also be desirable if at all feasible, 2) for the first 3 to 4 years after construction, at the end of each summer or in early fall, and 3) then every 2-3 years in late summer, until conditions stabilize.

20. There is not a well defined relationship among surface thaw settlement, pipe settlement and pipe movement. Differential thaw settlement of the pipe is still a significant issue and it is recommended that monitoring of pipe movement and condition be continued by the pipeline operator.

21. It is recommended that surface thaw settlement of the right-of-way continue to be addressed by remedial programs in areas where drainage and erosion problems may otherwise occur.

8.6 WOOD CHIP INSULATION

Key issues:
- slope stability
- novel technique

22. It is recommended that the slope monitoring program, combined with visual site observations on a monthly basis, should continue until 1995, ten years from pipeline start-up or as long as potential for instability continues. It is believed,

based on IPL's performance model, that the potential for slope instability due to thaw progression beneath the wood chip layers will be greatest during the 5-10 year period following wood chip placement.

23. It is recommended that observations of snow accumulation on the wood chip covered slopes be taken. They are essential in interpreting the temperature data recorded in and below the wood chips. The snow depth measurement stakes placed by the PTRM program in the fall of 1986 have been most useful.

24. It is recommended that the future use of wood chips to reduce thaw of permafrost consider methods to:

    a) Keep the wood chips dry throughout the year. This would reduce the high latent heat effect promoting winter thaw of the permafrost. Prevention of heavy snow accumulation may or may not be an alternative depending on the thickness of the wood chip layer.

    b) Restrict the movement of outside air entering the wood chip layer. This would reduce the aerobic microbiological heating action and degradation in the wood chips. There is a possibility that use of a reduced thickness of wood chips, the use of fire-killed wood or restricting the amount of aspen might achieve the same purpose.

8.7 DRAINAGE AND EROSION CONTROL

Key issues:
- erosion of ROW and adjacent terrain
- ditchline subsidence
- exposure and undermining of the pipe
- sediment input to streams
- ponding and drainage diversion

It is likely that erosion control will continue to require attention on the Norman Wells Pipeline, particularly in regard to the impedance of cross-drainage in terrain units subject to thaw settlement. A number of specific recommendations may be made on the basis of monitoring during the period 1983-1988. Many of these recommendations may be applied to future northern pipeline projects since, to a great extent, drainage and erosion control problems in northern terrain are independent of specific engineering design criteria. Recommendations are divided according to their relevance to (a) design, (b) construction, (c) operation and maintenance, and (d) monitoring:

(a) Design:

25. It is recommended that stream crossings (pipe burial depth, sag point locations) be designed for a maximum flood based on geological/geomorphic evidence, hydrological models, and considerations based on climate change scenarios. In northern regions, the calculation of flood frequency is limited by the paucity of hydrological and meteorological data. Major floods affecting Hodgson Creek (1986, 1988) and Ochre River (1988) pipeline crossings have illustrated the difficulty in predicting hydrologic regimes within the Mackenzie Valley, and argue for a conservative approach to flood estimation and conservative burial of pipe across floodplains.

26. It is recommended that design criteria used to determine the requirement and spacing of drainage diversion berms on low-angled slopes be re-evaluated, in areas where the ROW extends perpendicular to the regional slope for distances greater than 500 m. At several locations south of Fort Simpson, water entering the ROW from ephemeral water courses and seeps has become concentrated along the ditchline. This has resulted in erosion of backfill and, in some cases, exposure of the pipe.

27. It is recommended that the effects of icings and ice damming be considered in the design of stream crossings. Within small confined drainage channels, these effects can significantly raise flood levels, and disturb slope and streambank protection structures, and confine and direct flow to vulnerable sections of riverbank.

(b) Construction:

28. It is recommended that all water crossing streambanks and approach slopes should be covered with rip-rap at the time of construction, up to the maximum predicted flood level wherever practicable.

29. It is recommended that drainage diversion berms be constructed using materials, for example sandbags, which can adjust to irregularly subsiding terrain. Rigid berms made from plywood sheets or logs may fail to control flow as the ground surface subsides around and beneath them.

30. It is recommended that careful consideration be given to choice of cover material used in sandbags, to prevent premature disintegration of the bag leading to diversion berm failure and inadequate control of surface runoff.

31. It is recommended that small water courses be identified and flagged during the summer preceding construction. During

winter construction, it is often hard to distinguish these features and as a result required diversion berms may be incorrectly positioned or not used at all.

32. It is recommended that, in cases where snow is removed from the ROW, it should be placed or dispersed in such a way that the impact of additional snowmelt runoff is reduced. In cases where runoff is concentrated over small sloping areas of ROW it may contribute to erosion and slope instability.

(c) Operation and maintenance:

33. It is recommended that in cases where the ROW is used for vehicle access, erosion and drainage control structures can withstand traffic levels, or are replaced or repaired if damaged. If these precautions are not taken, then maintenance activities may actually create additional or new erosion problems.

34. It is recommended that where summer maintenance activity is undertaken, precautions are taken to ensure that vehicle tracks do not form incipient lines of drainage. Again, this may result in the development of additional or new erosion problems.

(d) Monitoring:

35. It is recommended that erosion control structures be monitored frequently (weekly or more often) and maintained during the first few years following construction, particularly after major summer storm events and spring snowmelt runoff. Possible misplacement of berms, omission of watercourses from the design, and reduced vegetation cover renders the ROW surface particularly vulnerable to erosion during this period. It should be noted that the period for frequent monitoring and maintenance may be longer where vegetation recovery is slower; this depends for example on latitude, elevation, degree of disturbance and extent of restoration program.

36. It is recommended that the placement of diversion berms be assessed immediately after snowmelt following winter construction. Because they may be built on a snow covered and/or graded surface, it is not always possible to detect minor surface irregularities which may reduce or negate the effectiveness of the berms following snowmelt.

37. It is recommended that berm structures be monitored closely in areas of subsiding terrain. In the early years, ditchline subsidence may require the rebuilding or repositioning of many

diversion berms. Later, more general thaw settlement of the ROW may require similar remedial action.

38. It is recommended that mitigation structures at water crossings be monitored closely throughout the lifetime of the project, and particularly following flood events related to spring runoff or intense summer rainstorms.

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APPENDIX A

GLOSSARIES

Table A-1: Permafrost related terms

Table A-2: Pipeline related terms

Table A-1. Glossary of permafrost related terms.

(from "Glossary of Permafrost and Ground-Ice Terms", National Research of Canada, Technical Memorandum 142, 1988, 156 pp.)

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active layer - The top layer of ground subject to annual thawing and freezing in areas underlain by permafrost.

depth of thaw - The minimum distance between the ground surface and frozen ground at any time during the thawing season.

freezing (of ground) - The changing of phase from water to ice in soil or rock.

freezing front - The advancing boundary between frozen (or partially frozen) ground and unfrozen ground.

freezing-point depression - The number of degrees by which the freezing point of an earth material is depressed below 0°C.

freezing pressure - The positive (heaving) pressure developed at ice-water interfaces in a soil as it freezes.

frost, seasonal - The occurrence of ground temperatures below 0°C for only part of the year.

frost bulb - A more or less symmetrical zone of frozen ground formed around a buried chilled pipeline or beneath or around a structure maintained at temperatures below 0°C.

frost heave - The upward or outward movement of the ground surface (or objects on, or in the ground) caused by the formation of ice in the soil.

frost-stable ground - Ground (soil or rock) in which little or no segregated ice will form (causing frost heave) under the required conditions of moisture supply and temperature.

frost-susceptible - Ground (soil or rock) in which segregated ice will form (causing frost heave) under the required conditions of moisture supply and temperature.

frozen ground - Soil or rock in which part or all of the pore water consists of ice.

ground thermal regime - A general term encompassing the temperature distribution and heat flows in the ground and their time - dependence.

ice, excess - The volume of ice in the ground which exceeds the total pore volume that the ground would have under natural unfrozen conditions.

ice, ground - A general term referring to all types of ice formed in freezing and frozen ground. (ice lens, ice wedges, pingo ice).

ice, segregated - Ice formed by the migration of pore water to the frozen fringe where it forms into discrete layers.

ice content - The amount of ice contained in frozen or partially frozen soil or rock.

ice lens - A dominantly horizontal, lens-shaped body of ice of any dimension.

latent heat - The volumetric latent heat of fusion is the amount of heat required to melt the ice (or freeze the water) in a unit volume of soil.

palsa - A peaty permafrost mound possessing a core of alternating layers of segregated ice and peat or mineral soil material.

Table A-1. (continued)

peatland - Peat-covered terrain

peat plateau - A generally flat-topped expanse of peat, elevated above the general surface of a peatland, and containing segregated ice that may or may not extend downward into the underlying mineral soil.

permafrost - Ground (soil or rock) that remains at or below 0°C for at least two years.

permafrost, continuous - Permafrost occurring everywhere beneath the exposed land surface throughout a geographic region with the exception of widely scattered sites, such as newly deposited unconsolidated sediments, where the climate has just begun to influence the ground thermal regime causing the formation of continuous permafrost.

permafrost, discontinuous - Permafrost occurring in some areas beneath the exposed land surface throughout a geographic region where other areas are free of permafrost. Near its northern boundary, discontinuous permafrost is widespread, whereas near its southern boundary it occurs in isolated patches or islands and is commonly referred to as "sporadic".

permafrost, equilibrium - Permafrost that is in thermal equilibrium with the existing mean annual ground-surface or sea-bottom temperature and with the geothermal heat flux.

permafrost, ice-rich - Permafrost containing excess ice.

permafrost, thaw-sensitive - Perennially frozen ground which, upon thawing, will experience significant thaw settlement and suffer loss of strength to a value significantly lower than that for similar material in an unfrozen condition. Ice-rich permafrost is thaw-sensitive.

permafrost, thaw-stable - Perennially frozen ground which upon thawing, will not experience either significant thaw settlement or loss of strength.

permafrost aggradation - A naturally or artificially caused increase in the thickness and/or a real extent of permafrost.

residual thaw layer - A layer of thawed ground between the seasonally frozen ground and the permafrost table (the upper boundary of permafrost).

solifluction - Slow downslope flow of saturated unfrozen earth materials.

talik - A layer or body of unfrozen ground in a permafrost area.

thaw basin - A depression of the permafrost table created by naturally induced thawing (e.g. beneath lakes or rivers that do not freeze to the bottom in winter).

thaw bulb - A more or less symmetrical area of thaw in permafrost surrounding a man-made structure.

Table A-1. (continued)

thaw consolidation - Time-dependent compression resulting from thawing of frozen ground and subsequent drainage of pore water.

thaw settlement - Compression of the ground due to thaw consolidation.

thaw slumping - A slope failure mechanism characterized by the melting of ground ice, and downslope sliding and flowing of the resulting debris.

thawing index - The cumulative number of degree-days above 0°C for a given time period.

thermal erosion - The erosion of ice-rich permafrost by the combined thermal and mechanical action of moving water.

thermokarst - The process by which characteristic land forms result from the thawing of ice-rich permafrost.

thermokarst terrain - the irregular topography resulting from the melting of excess ground ice and subsequent thaw settlement.

thermosyphon -A passive heat transfer device installed to remove heat from the ground.

water, pore - Water occurring in the pores of soils and rocks.

water content, total - The total amount of water (unfrozen water & ice) contained in soil or rock.

zero curtain -The period of time during which a nearly constant temperature, very close to the freezing point, exists during annual freezing (and occasionally during thawing) of the active layer.

Table A-2. Glossary of some pipeline related terms.

backfill - excavated material from the ditch that was placed back over pipeline.
  native, local - backfill replaced from original location
  select - other material usually non ice-rich and more stable, from quarries

buckling - change in pipe cross section due to longitudinal bending, which may be promoted by differential soil movement along the pipe axis

chainage, plan, - preliminary survey distances before construction (Norman Wells = kp 0)
  "as built" final survey distances after construction including any alignment changes (final length 869.48 km)

curvature - aspect of pipe's displaced profile with respect to its longitudinal profile (change in slope)

pig - device sent down the inside of a pipeline to perform various functions as in a scraper pig to clean the inside of the pipe
  "super pig" a pig instrumented with tools to aid in internal monitoring of the pipeline conditions
  "caliper pig" measures ovality of the cross-section of the pipe with mechanical calipers to detect circumferential wrinkles (used on TAPS to detect wrinkles)

push outs - areas adjacent to the R.O.W., used for disposal of unstable excavated ditch spoil

roach - high mound of unconsolidated spoil or backfill placed over the pipe and ditch area (during winter construction may include ice and snow)

sag bend - deeper buried portion of pipe below a water crossing or channel

sag points - points at which the pipeline is brought up from deeper burial below a water crossing

shoo fly - travel detour around steep slopes or water crossings

spoil - material excavated from the pipeline ditch

stress - generated from operating and bending conditions

throughput - volume of oil flow per unit time

weights - structures placed on the pipe to prevent buoyancy (e.g. saddle weights)

wrinkles - may result from bending of the pipe, on the compression side of the pipe

APPENDIX B

SCHEDULES OF FIELD MEASUREMENTS AND OBSERVATIONS

TABLE B-1. Dates of permafrost and terrain monitoring field work from 1983 through 1988 (main emphasis on thermal data collection).

DATES	OBSERVERS	PURPOSE
1983		
May 10-12	J. Pilon, K. MacInnes	Preliminary site selection (INAC, EMR)
October 5-6	J. Pilon, A. Judge K. MacInnes	Revised site selection (INAC, EMR)
1984		
April 28-30	J. Pilon, D. Harry, K. MacInnes, J. Hayes	Data-all sites (INAC, EMR)
June 5-8	D. Harry, K. MacInnes	Data-all sites (INAC, EMR)
June 21-23	J. Pilon, M. Burgess	Data-all sites (EMR)
July 13-18	K. MacInnes	Data-all sites (INAC)
August 9-14	J. Pilon, K. MacInnes, H. Madill	Data-all sites (INAC, EMR)
September 18-27	K. MacInnes, D. Harry	Data-all sites (INAC, EMR)
September 26-October 3	J. Pilon, M. Burgess	Data-all sites (EMR)
November 23-28	M. Burgess, J. Pilon	Data-all sites (EMR)
1985		
January 4, 26-20	A. Nixon, B. Hoover, J. Hayes	Data (INAC)
February 14	K. MacInnes	Check Table Mt. Site (INAC)
February 19-25	J. Pilon, A. Judge	Data-all sites (EMR)
March 5-9	K. MacInnes, A. McRobert	Data-all sites (INAC)
March 27-30	K. MacInnes	Install new cables. Southern Data (INAC)
April 9,10	J. Hayes	Northern Data (INAC)
April 16,17	A. Nixon, B. Hoover, K. Beraska	Southern Data (INAC)
May 21-29	J. Pilon	Data-all sites (EMR)
June 4-9	K. MacInnes, D. Harry	Data-all sites (INAC, EMR)
July 15-20	K. MacInnes, S. Dupras	Data-all sites (INAC)
August 9-14	K. MacInnes, L. Schmidt, J. Hayes	Data-all sites (INAC)
September 4-9	D. Harry, K. MacInnes	Data-all sites (INAC, EMR)
October 11-17	M. Burgess, V. Allen	Data-all sites (EMR)

Table B-1. (cont'd)

DATES	OBSERVERS	PURPOSE
1985		
November 13,15	L. Schmidt, N. Sancartier	Northern Data (INAC)
November 20	J. Hayes, W. LaFleur	Southern Data (INAC)
December 10,18,19	N. Sancartier, L. Schmidt	Northern Data (INAC)
December 12,13,16	K. Beraska, B. Hoover, J. Hayes, D. Trudeau, W. Lafleur	Southern Data (INAC)
1986		
January 14,17	P. Rivard, N. Sancartier, L. Schmidt	Northern Data (INAC)
January 13-15	B. Hoover, W. Lafleur K. Beraska, D. Trudeau	Southern Data (INAC)
February 21	D. Elliott	Northern Data (INAC)
February 19,20	J. Hayes, W. Lafleur	Southern Data (INAC)
March 3-5	K. MacInnes, J. Pilon, W. Pollard	Northern Data (INAC, EMR)
March 12,24,26	D. Trudeau, W. Lafleur, K. Beraska	Southern Data (INAC)
April 9,10,12	D. Trudeau, B. Hoover, W. Lafleur	Southern Data (INAC)
April 29	B. Hoover (with IPL)	Southern pipe Thermistor (INAC)
April 30	L. Schmidt, N. Sancartier	Northern Data (INAC)
May 23-28	M. Burgess, W. Pollard	Data-all sites (EMR)
June 19-23	D. Harry, K.MacInnes	Data-all sites (INAC, EMR)
June 27,28	A. Judge, J.Pilon	Radar survey, Great Bear (EMR)
July 14-19	K. MacInnes	Data-all sites (INAC)
August 1-11	K. MacInnes, C.Tarnocai, D. Kroetsch	Data-all sites (INAC) Install soil probes (AG CAN)
September 25-30	K. MacInnes, F. Adelm, H. Baker	Data-all sites (INAC, NRC)
October 22-30	M. Burgess, V. Allen	Data-all sites (EMR)
November 12	D. Elliott, L. Schmidt P. Rivard	Northern data (INAC)
November 19-20	D. Trudeau, B. Hoover	Southern data (INAC)
December 10	L. Schmidt, D. Elliott	Northern data (INAC)
December 16-17,19-22	D. Trudeau, B. Hoover	Southern data (INAC)
1987		
January 15-16	P. Rivard, L. Schmidt	Northern data (INAC)
January 16, 20-21	B. Hoover, D. Trudeau	Southern data (INAC)
February 4-9	J. Pilon, A. Judge	All sites (EMR)

Table B-1. (cont'd)

DATES	OBSERVERS	PURPOSE
1987		
March 9-15	K. MacInnes, A. McRobert	All sites (INAC)
April 15-16	L. Schmidt, P. Rivard, D. Elliott	Northern data (INAC)
April 9, 13	D. Trudeau	Southern data (INAC)
May 22-27	M. Burgess, A. Wilkinson	All sites (EMR)
June 15-21	H. Baker, K. MacInnes	All sites (NRC, INAC)
July 9-13	K. MacInnes, A. McRobert D. Trudeau	All sites (INAC)
August 14-20	C. Tarnocai, K. MacInnes	All sites (AG CAN, INAC)
September 14-21	D. Harry, K. MacInnes	All sites (EMR, INAC)
October 1-7	M. Burgess, V. Allen	All sites (EMR)
November 12-13	D. Elliott, L. Schmidt	Northern data (INAC)
November 12-13	D. Trudeau, A. Boyer P. Boyle	Southern data (INAC)
December 14-16	D. Elliott	Northern data (INAC)
December 15, 16, 18	D. Trudeau, A. Boyer	Southern data (INAC)
1988		
January 14, 22	D. Elliott, A. McRobert	Northern data (INAC)
January 18-19	A. Boyer, D. Trudeau	Southern data (INAC)
February 8, 10, 12	A. Boyer, D. Trudeau	Southern data (INAC)
March 7-11	K. MacInnes, D. Trudeau	All sites (INAC)
April 14, 18	D. Elliott, L. Elliott	Northern data (INAC)
April 19-20	A. Boyer, F. McGowan	Southern data (INAC)
May 25 - June 1	K. MacInnes, C. Tarnocai, D. Kroetsch	All sites (INAC, AGCAN) Install XL-800 loggers
July 5-10	M. Burgess, K. MacInnes	All sites (INAC, EMR)
August 10-11	K. MacInnes, A. McRobert, J. Ngai	km 225-608 (INAC)
August 28	A. Judge	km 0- 270 (EMR)
September 12-18	D. Harry, K. MacInnes, P. Kurfurst, C. Tarnocai	All sites (EMR, INAC, AG CAN)
September 16-20	L. White	Install heat flow meter, km 19 (NRC)
October 22-28	M. Burgess, V.Allen	All sites (EMR) Install logger at 12B
December 7-9	A. Boyer, J. Ginter	Southern sites (INAC)
December 13-14	J. Bowen, D. Elliott	Northern data (INAC)

Notes:

Observers include staff from Indian and Northern Affairs Canada (INAC) Region and Districts, Energy, Mines and Resources (EMR), Agriculture Canada (AG CAN) and National Research Council (NRC). Northern data refers to sites from km 0 to 79. Southern data refers to site from km 270 to 608. All sites refers to sites from km 0 to 819.

TABLE B-2. STATISTICS ON TEMPERATURE CABLE READINGS

SITE	CABLE NO.	MONTH** INSTALLED	MONTHS WITHOUT DATA****	TOTAL NO. OF READINGS* 84	85	86	87
84-1	PT***	6/84	8/84,9/84,10/84 12/84,1/85,7/86	3	13	12	12
	T1	6/84	12/84	6	13	12	13
	T2	9/84	12/84	3	12	12	13
	T3	9/84	12/84	3	13	12	13
	T4	6/84	12/84	6	13	12	13
	T5	9/84	12/84	3	13	12	13
84-2A	PT	3/84	5/84,11/84,12/84 11/85,12/85,1/86 2/86,11/86	10	13	11	12
	T1+	6/84	12/84,3/85,4/85	6	10	13	10
	T2+	8/84	12/84	4	12	13	10
	T3+	8/84	12/84	3	12	13	10
	T4	6/84	12/84,4/85,11/85 12/85,1/86,2/86 3/86,4/86,11/86,12/86	6	9	6	10
	HT140	5/87					8
	HT138	9/87		-	-	-	4
	HT153	9/87	12/87	-	-	-	3
84-2B	PT	3/84	5/84,9/84,12/84 1/85,1/86,2/86	10	12	14	12
	T1	8/84	12/84,2/86,3/87	4	12	11	11
	T2	6/84	12/84,2/86,3/87	6	12	11	11
	T3	6/84	7/84,12/84,2/86 9/86,1/87,4/87	6	12	10	10
	T4	9/84	12/84,2/86,9/86 1/87,4/87	3	12	11	10
84-2C	PT	3/84	5/84,7/8412/84 5/85,2/86	10	13	16	12
	T1	6/84	7/84,12/84,2/86	6	12	11	12
	T2	8/84	12/84,2/86	4	12	11	12
	T3	6/84	7/84,12/84,2/86	5	12	11	12
	T4	9/84	10/84,12/84,2/86	2	12	11	12
84-3A	PT	3/84	5/84,10/84,12/84 2/86	7	15	14	12
	T1+	6/84	7/84,12/84	5	12	13	9

*: MAY BE MORE THAN ONE READING PER MONTH **: AND/OR FIRST READING
***: PT = PIPE THERMISTOR STRING
****: DUE EITHER TO LACK OF COLLECTION OR TO POOR DATA QUALITY
+: CABLE CONNECTED TO DATA LOGGER; some of 1987 data still on tape

Table B-2 (cont'd)

SITES	CABLE NO.	MONTH** INSTALLED	MONTHS WITHOUT DATA****	TOTAL NO. OF READINGS* 84	85	86	87
84-3A	T2+	9/84	10/84,12/84,7/87	4	12	11	12
	T3+	9/84	10/84,12/84,7/87	2	12	13	8
	T4+	6/84	7/84,12/84,7/87	5	12	13	8
84-3B	PT***	3/84	5/84,7/84,9/84 12/84,2/86	9	16	17	12
	T1	9/84	12/84,2/86,9/87	3	12	11	11
	T2	9/84	12/84,2/86	3	12	11	12
	T3	9/84	12/84,2/86	3	12	11	12
	T4	9/84	12/84,2/86	3	12	11	12
85-7A	PT	2/85	11/85,12/85,1/86 2/86	-	11	14	6
	T1+	4/85	6/86,7/86,8/86,9/86	-	9	9	6
	T2+	4/85	6/86,7/86,8/86,9/86	-	9	9	6
	T3+	4/85	6/85	-	7	14	6
	T4+	3/85		-	10	14	6
	HA108	4/86		-	-	9	12
	HA111	4/86		-	-	9	12
85-7B	PT	2/85	11/85,12/85,1/86 2/86,4/86	-	12	11	13
	T1+	4/85	6/86,7/86,8/86,9/86	-	9	9	6
	T2+	3/85	6/86,7/86,8/86,9/86	-	11	9	6
	T3+	3/85	6/86,7/86,8/86,9/86	-	11	9	6
	T4+	3/85	6/86,7/86,8/86,9/86	-	11	9	6
	HA110	4/86	4/87	-	-	9	11
	HA129	10/86	11/86,12/86,1/87 2/87	-	-	1	10
	HA132	10/86	11/86,12/86,1/87 2/87	-	-	1	10
85-7C	PT	3/85	11/85,12/85,1/86 2/86,4/86	-	10	11	12
	T1+	4/85	11/85,12/85,1/86 2/86	-	7	9	10
	T2+	4/85	11/85,12/85,1/86 2/86	-	7	9	10
	T3+	4/85	11/85,12/85,1/86 2/86	-	7	9	10
	T4+	3/85	11/85,12/85,1/86 2/86,4/86,4/87	-	9	9	9
	HA109	4/86	12/86	-	-	8	12

Table B-2. (cont'd)

SITES	CABLE NO.	MONTH** INSTALLED	MONTHS WITHOUT DATA ****	TOTAL NO. OF READINGS* 84	85	86	87
84-4A	PT***	3/84	5/84,8/84,11/84 12/84,1/85,2/85 4/85	6	11	15	12
	T1(OLD)	9/84	12/84,7/85,11,85 12/85	3	10	-	-
	T1(NEW)	11/85		-	2	12	12
	T2	9/84	12/84,1/85,4/86 4/87	3	12	11	11
	T3	9/84	12/84,1/85	4	12	12	12
	T4	9/84	12/84,1/85	4	12	12	12
84-4B	PT	3/85	5/85,10/85	-	9	13	12
	T1(OLD)	9/84	10/84,12/84	2	-	-	-
	T1(NEW)	2/85	4/86	-	11	11	12
	T2	9/84	10/84,12/84,1/85 4/86	3	12	11	12
	T3	9/84	10/84,12/84,1/85	2	12	12	12
	T4	9/84	10/84,12/84,1/85	2	12	12	12
85-8A	PT	3/85	4/85	-	12	14	12
	T1	3/85	4/85	-	11	12	12
	T2	3/85	8/87	-	11	12	12
	T3	3/85		-	11	12	12
	T4	3/85		-	11	12	12
85-8B	PT	3/85		-	13	15	12
	T1	3/85		-	11	12	12
	T2	3/85		-	11	12	12
	T3	3/85		-	11	12	12
	T4	3/85		-	11	12	12
85-8C	PT	3/85	3/87	-	13	14	11
	T1	3/85		-	11	12	12
	T2	3/85	3/86	-	10	11	12
	T3	3/85	3/86	-	11	12	12
	T4	3/85		-	11	12	12
85-9	PT	3/85		-	12	15	12
	T1	3/85		-	11	12	12
	T2	3/85		-	11	12	12
	T3	3/85		-	10	12	12
	T4	3/85		-	10	12	12

Table B-2. (cont'd)

SITES	CABLE NO.	MONTH** INSTALLED	MONTHS WITHOUT DATA ****	TOTAL NO. OF READINGS* 84	85	86	87
85-10A	PT***	3/85		-	13	13	12
	T1	3/85	1/87	-	10	12	11
	T2	3/85	1/87	-	10	12	11
	T3	3/85	1/87	-	10	12	11
	T4	3/85	1/87	-	10	12	11
85-10B	PT	3/85		-	13	13	12
	T1	3/85	1/87	-	10	12	11
	T2	3/85	1/87	-	10	12	11
	T3	3/85	1/87	-	10	12	11
	T4	3/85	1/87	-	10	12	11
85-11	PT	3/85		-	13	13	12
	T1	3/85		-	10	12	12
	T2	3/85		-	10	12	12
	T3	3/85		-	10	12	12
	T4	3/85		-	10	12	12
85-12A	PT	3/85		-	13	13	12
	T1	3/85	3/87	-	10	12	11
	T2	3/85		-	10	12	12
	T3A	3/85	11/85,12/85,1/86 2/86,3/86	-	7	9	12
	T3	3/87	4/87	-	-	-	9
	T4	3/85	3/86	-	10	11	12
85-12B	PT	3/85		-	13	14	12
	T1	3/85		-	10	12	12
	T2	3/85		-	10	12	12
	T3	4/85		-	9	12	12
	T4	3/85		-	10	12	12
	HA133	6/87	11/87,12/87	-	-	-	5
	HA134	6/87	11/87,12/87	-	-	-	5
85-13	A,B,C	3/85	11/85,12/85,1/86 2/86,3/86,4/86, 11/86,12/86,4/87 7/87,11/87,12/87	-	8	6	8
84-5A	PT	3/84	5/84,10/84,12/84 1/85,2/85,4/85,11/85 12/85,1/86,2/86,3/86 11/86,12/86,1/87 4/87,11/87,12/87	7	9	8	7

Table B-2. (cont'd)

SITES	CABLE NO.	MONTH** INSTALLED	MONTHS WITHOUT DATA****	TOTAL NO. OF READINGS* 84	85	86	87
84-5A	T1,T2	9/84	10/84,12/84,1/85 4/85,11/85,12/85 1/86,2/86,3/86,4/86 11/86,12/86,1/87 4/87,11/87,12/87	2	9	6	8
	T3	11/84	12/84,1/85,4/85 11/85,12/85,1/86 2/86,3/86,4/86 11/86,12/86,1/87 4/87,11/87,12/87	1	9	6	8
	T4	9/84	10/84,12/84,1/85 4/85,11/85,12/85 1/86,2/96,3/86,4/86 11/86,12/86,1/87 4/87,11/87,12/87	2	9	6	8
84-5B	PT***	3/84	5/84,10/84,12/84 1/85,4/85,11/85 12/85,1/86,2/86 3/86,11/86,12/86 1/87,4/87,11/87 12/87	7	10	7	8
	T1(OLD)	11/84	12/84,1/85,4/85 11/85,12/85,1/86 2/86,3/86,4/86	1	9	6	-
	T1(NEW)+	10/86	11/86,12/86,1/87 3/87,4/87,7/87,9/87	-	-	-	6
	T2(OLD)	9/84	10/84,12/84,1/85 4/85,11/85,12/85 1/86,2/86,3/86,4/86	2	9	6	-
	T2(NEW)+	10/86	11/86,12/86,1/87 3/87,4/87,7/87,9/87	-	-	-	6
	T3(OLD)	9/84	10/84,12/84,1/85 4/85,11/85,12/85 1/86,2/86,3/86,4/86	2	9	6	-
	T3(NEW)+	10/86	11/86,12/86,1/87 3/87,4/87,7/87	-	-	-	6
	T4(OLD)	11/84	12/84,4/85,7/85 11/85,12/85,1/86 2/86,3/86,4/86	1	9	-	6
	T4(NEW)+	10/86	11/86,12/86,1/87 3/87,4/87,7/87	-	-	-	6

Table B-2. (cont'd)

SITES	CABLE NO.	MONTH** INSTALLED	MONTHS WITHOUT DATA****	TOTAL NO. OF READINGS* 84	85	86	87
84-6	PT***	3/84	4/84,5/84,10/84 12/84,1/85,4/85 11/85 to 3/86 12/86,1/87,4/87 11/87,12/87	6	11	7	8
	T1	9/84	10/84,12/84,1/85 4/85,11/85 to 4/86 11/86,12/86,1/87 4/87,11/87,12/87	2	8	6	8
	T2	9/84	10/84,11/84,12/84 1/85,4/85,11/85 to 4/86, 11/86 12/86,1/87,4/87 11/87,12/87	1	9	6	8
	T3	9/84	10/84,11/84,12/84 1/85,4/85,11/85 to 4/86, 11/86 12/86,1/87,4/87 11/87,12/87	1	9	6	8
	T4	9/84	10/84,11/84,12/84 1/85,4/85,11/85 to 4/86, 11/86 12/86,1/87,4/87 11/87,12/87	1	9	6	8
	T5(OLD)	11/84	12/84,1/85,4/85 to 8/85,10/85 to 4/86,6/86 to 10/86	1	4	1	-
	T5(NEW)	10/86	11/86 to 1/87, 3/87 to 9/87 11/87,12/87	-	-	-	2
KEE SCARP	HT137	6/87	7/87,8/87	-	-	-	7
	HT139	9/87		-	-	-	4
	HT152	9/87		-	-	-	4
KM 95.1		10/86	11/86 to 2/87 4/87,11/87,12/87	-	-	1	7
KM 135	HA127 HA128	10/86	11/86 to 2/87 4/87,11,/87,12/87	-	-	1	7
KM 470	HA131	2/87	4/87,12/87	-	-	-	9
	HA130	2/87	4/87	-	-	-	10

Table B-3. Soil temperature probe location and method of monitoring.

NO.	LOCATION (thermal fence)	KMP	NUMBER OF PROBES	METHOD OF MONITORING[1] (1986-1988)
1	Pump Station 1 (PS1)	0.02	2	manual
2	Canyon Creek (2A)	19.0	2	manual
3	Great Bear River (3A)	79.2	3	recorder
4	Table Mountain (7A)	271.2	2	recorder
5	Table Mountain (7B)	272.0	2	recorder
6	Trail River (4B)	478.1	2	manual
7	Manner's Creek (8A)	557.8	2	manual
8	Manner's Creek (8B)	558.2	2	manual
9	Manner's Creek (8C)	558.3	2	manual
10	Mackenzie Hwy. (10a)	588.3	2	manual
11	Jean Marie Creek (12B)	608.7	2	manual
12	Redknife Hills (13C)	682.6	2	manual
13	Petitot River N. (5B)	783.3	2	manual

1. After May 1988, all locations were converted to data recorders except Manner's Creek 8B and 8C.

TABLE B-4. SCHEDULE OF TDR SURVEYS

FENCE	SEPT. 84*	NOV. 84*	MAY 85	(OCT. 85, MAY 86, OCT. 86, MAY 87 & OCT. 87)**
84-1	B,C	-	-	B,C,P
84-2A	C	C	*C	B,C,P
84-2B	B,C,P	C,P	*B,C,P	B,C,P
84-2C	B,C,P	-	*B,C,P	B,C,P
84-3A	B,C,P	C	*B,C,P	B,C,P
84-3B	B,C,P	P	-	B,C,P
85-7A	-	-	-	B,C,P
85-7B	-	-	-	B,C,P
85-7C	-	-	-	B,C,P
84-4A	B,C,P	-	**B,C,P	B,C,P
84-4B	B,C,P	B,C	**B,C,P	B,C,P
85-8A	-	-	-	B,C,P
85-8B	-	-	-	B,C,P
85-8C	-	-	-	B,C,P
85-9	-	-	-	B,C,P
85-10A	-	-	-	B,C,P
85-10B	-	-	-	B,C,P
85-11	-	-	-	B,C,P
85-12A	-	-	+B,C,P	B,C,P
85-12B	-	-	+B,C,P	B,C,P
85-13A	-	-	-	C
85-13B	-	-	-	C
85-13C	-	-	-	C
84-5A	B,C,P	C	**B,C,P	B,C,P
84-5B	B,C,P	B,C	**B,C,P	B,C,P
84-6	B,C,P	B,C	**B,C,P	B,C,P

B = OFF ROW C = CENTRE OF ROW P = NEAR PIPE TRENCH

* = 1, 3, 6 foot transmission lines only
** = 1, 2, 3, 4.5, 6 foot transmission lines
\+ = 2, 4.5 foot transmission lines only

TABLE B-5. SCHEDULE OF GROUND PROBING RADAR SURVEYS

FENCE	DEC. 83	JUNE 84	SEPT. 84	MAY 85	JUNE 86
84-1	KP 0.06	yes	yes	yes	----
84-2A	KP 19	yes	yes	yes	----
-2B	----	yes	yes	yes	----
-2C	----	yes	yes	yes	----
84-3A	KP 79	yes	yes	yes	yes
-3B	----	yes	yes	yes	yes
85-7A	KP 270	----	----	yes	----
-7B	----	----	----	yes	----
-7C	----	----	----	yes	----
84-4A	KP 477	yes	yes	yes	----
-4B	----	yes	yes	yes	----
85-8A	----	----	----	yes	----
-8B	----	----	----	yes	----
-8C	----	----	----	yes	----
85-9	KP 585	----	----	----	----
85-10A	----	----	----	yes	----
-10B	----	----	----	yes	----
85-11	----	----	----	yes	----
85-12A	----	----	----	yes	----
-12B	----	----	----	yes	----
85-13A	----	----	----	----	----
-13B	---	----	----	----	----
-13C	----	----	----	----	----
84-5A	----	yes	yes	yes	----
-5B	----	yes	yes	yes	----
84-6	----	yes	yes	yes	----

Note: Dec. 1983 surveys are pre-site establishment; hence their location is specified in terms of alignment sheet chainage.

APPENDIX C

PLOTS OF PIPE TEMPERATURE

AND

GROUND TEMPERATURE ON ROW ("1 m" sensor, deep cable)

AS A FUNCTION OF TIME

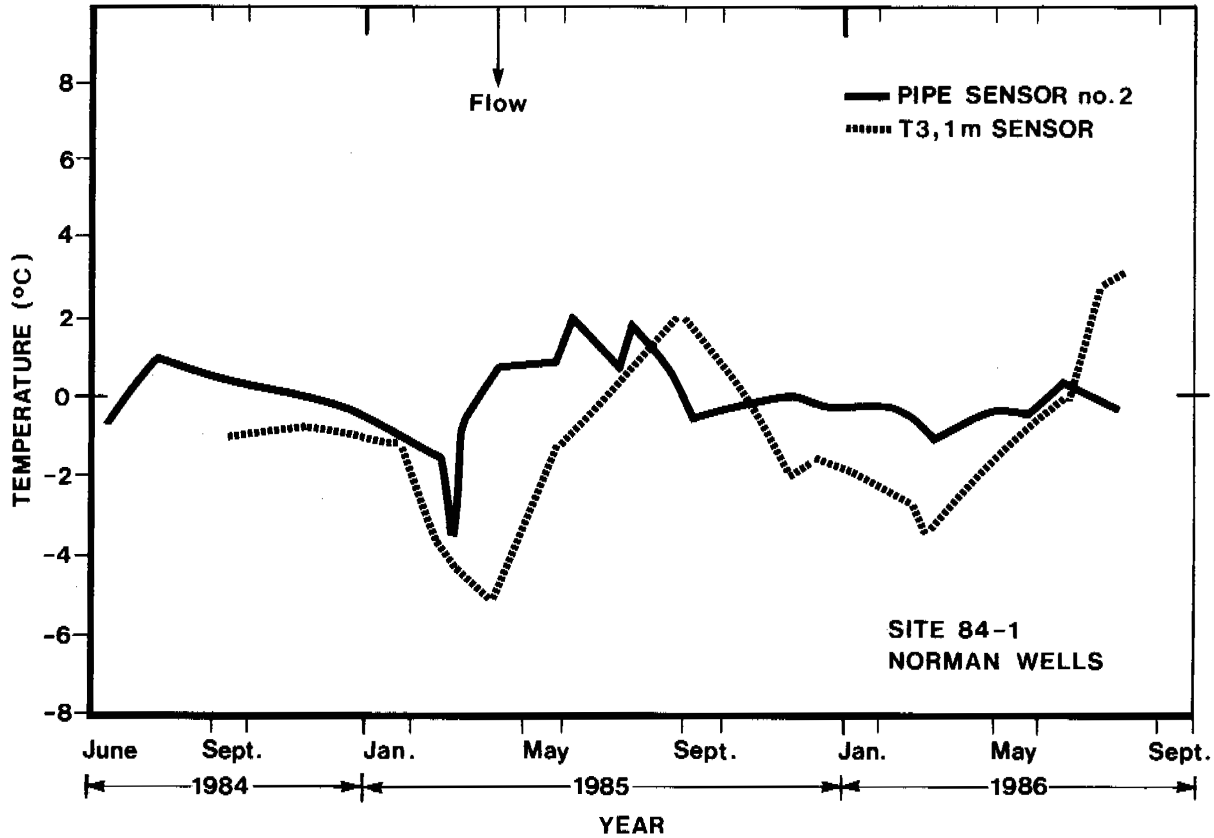
FOR EACH THERMAL FENCE

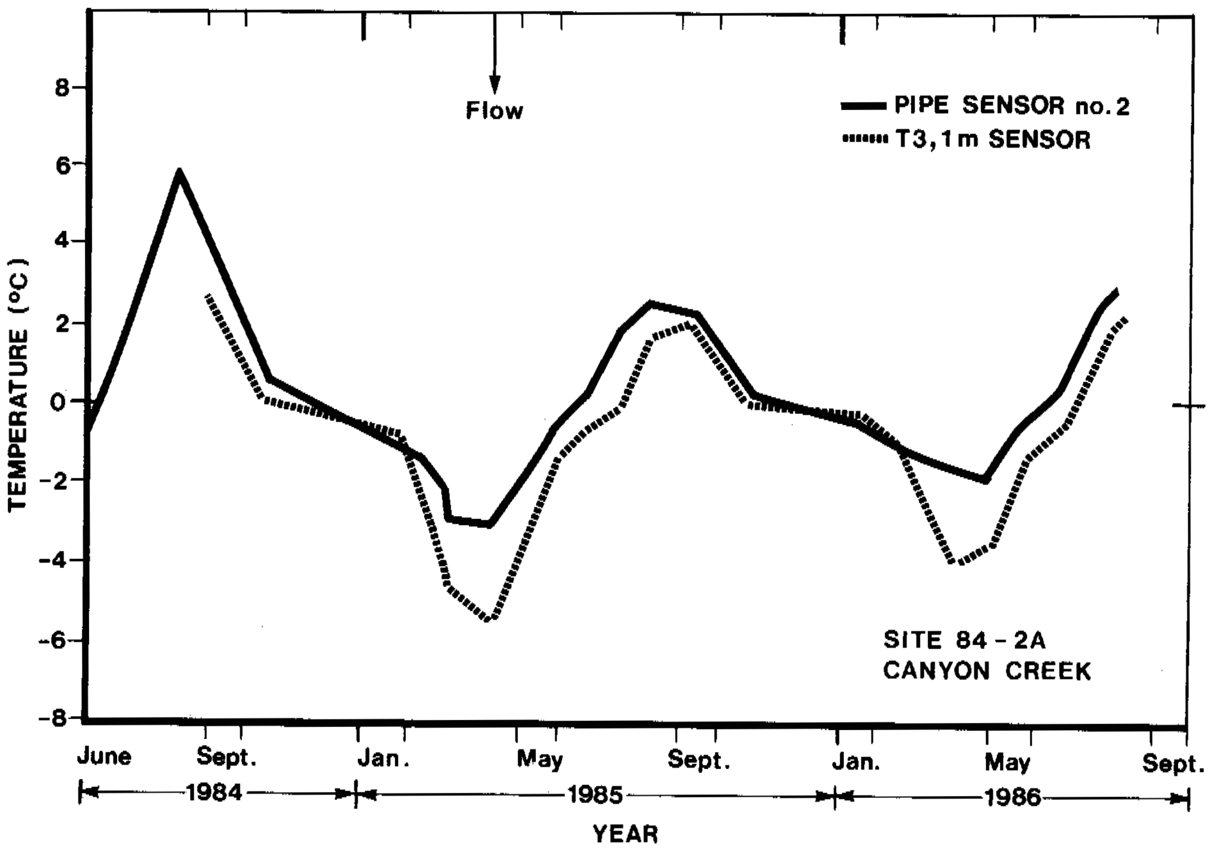
GENERAL COMMENTS

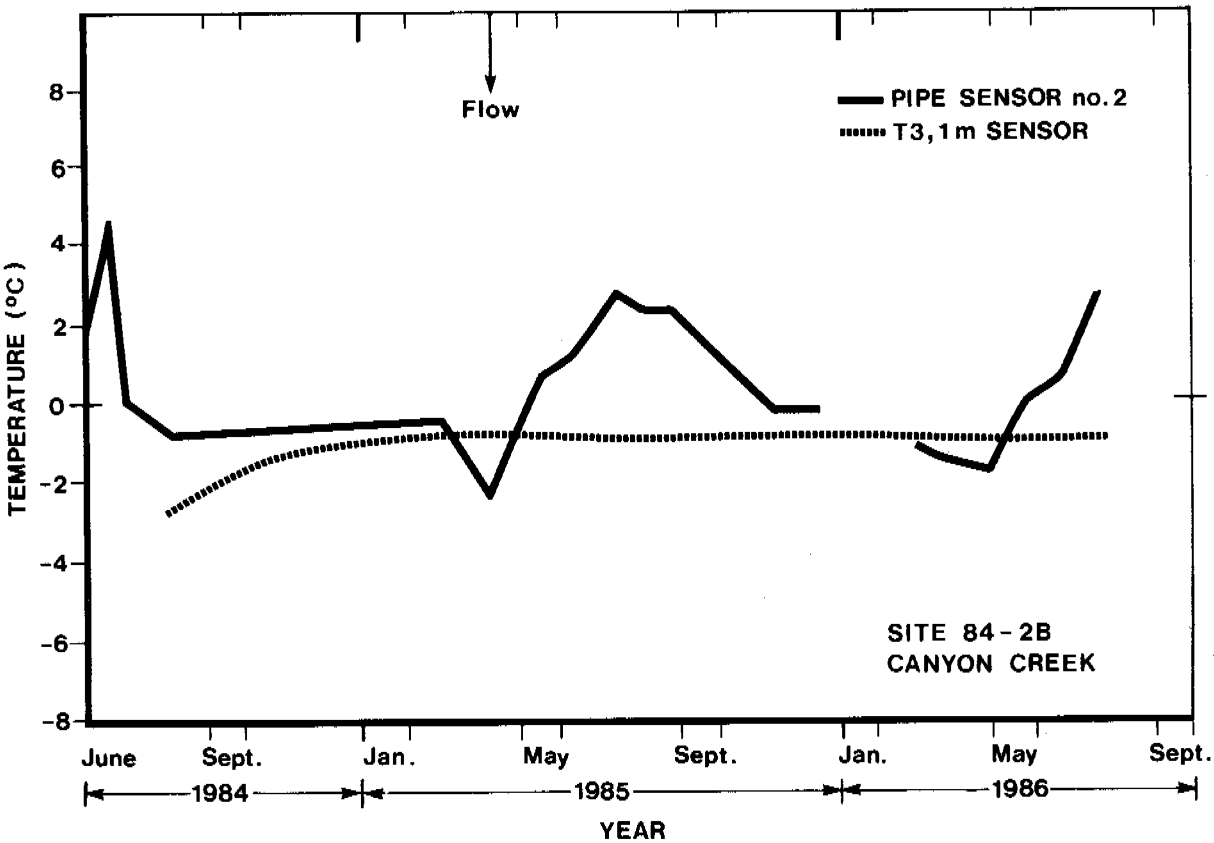
In order to compare the pipe thermal regime to the ambient ground thermal regime, ground temperatures from a similar depth on the ROW have been selected. The temperature cable located in the deep borehole on the ROW several metres (4 to 9) away from the trench was selected for the determination of ambient ground temperatures, as any trenching effects or any pipe thermal effects may have already been felt at the shallow cables located generally within a few metres of the trench. The first sensor on this deep cable was installed at a nominal depth of 1 m and lies at approximately the same burial depth as the pipeline (average depth of cover over the pipe, excluding roach, is 1 m).

Plots of pipe temperature versus time (using mid-pipe sensor #2) and ground temperature versus time (using the 1 m sensor at the deep ROW cable, generally cable T3), for each thermal fence instrumented with pipe temperature sensors are gathered in this Appendix. Data collected through September 1986 are plotted. Since the 5 pipe temperatures at a site are generally within a few tenths of a degree, only one of the sensors is drawn on these plots. Temperature measurements (both pipe sensors and ground temperature cables) are taken on average once a month, but plots are drawn as continuous lines for ease of comparison; where large (several months) data gaps exist, the lines are broken. The pipe sensor and ground temperature sensor are both initially at approximately the same depth; with time however their relative position and absolute depth may change as either the ground, or the trench backfill or the pipe move due to settlement or heave.

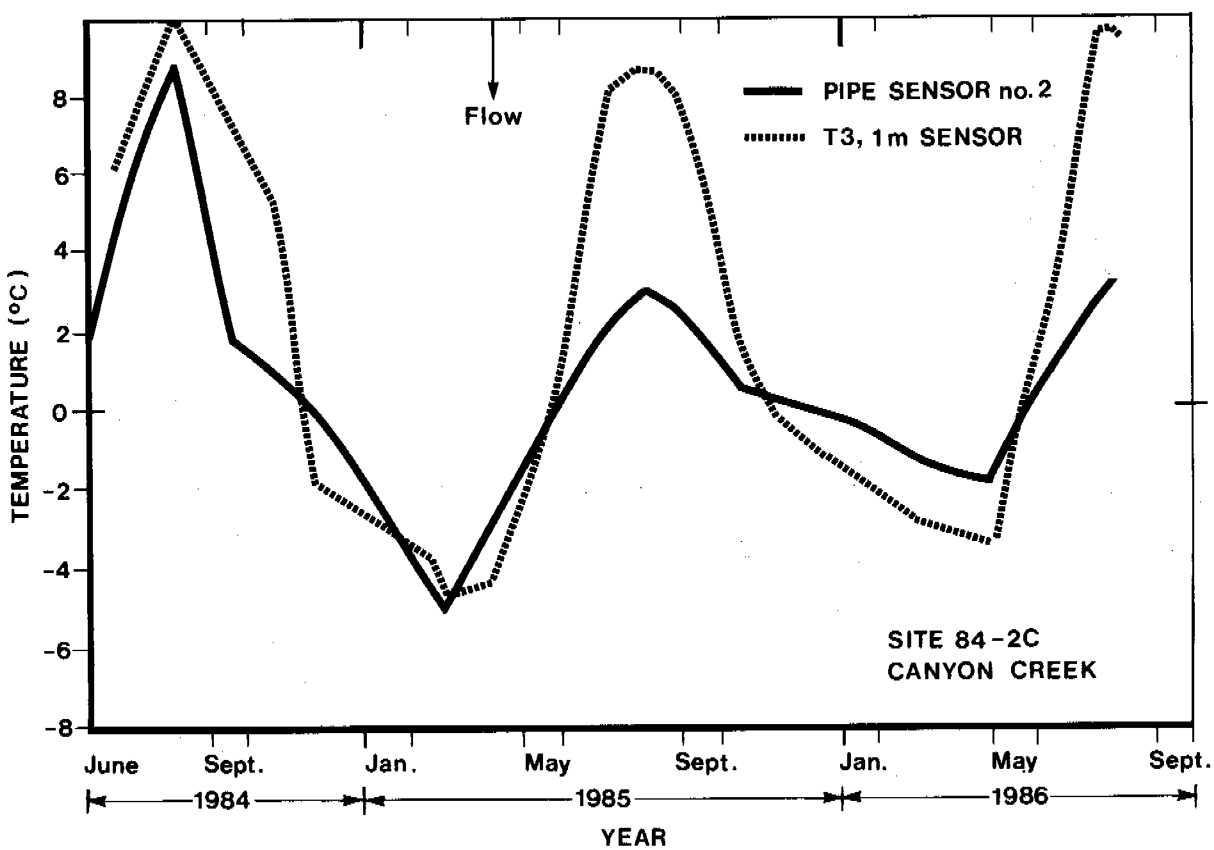
An indication of the range in trench subsidence and ROW subsidence at each fence surveyed topographically is given in Table 4-5.


Flow
PIPE SENSOR no.2
T3,1m SENSOR
TEMPERATURE (°C)
8
6
4
2
0
-2
-4
-6
-8
SITE 84-1
NORMAN WELLS
June
Sept.
Jan.
May
Sept.
Jan.
May
Sept.
1984
1985
1986
YEAR

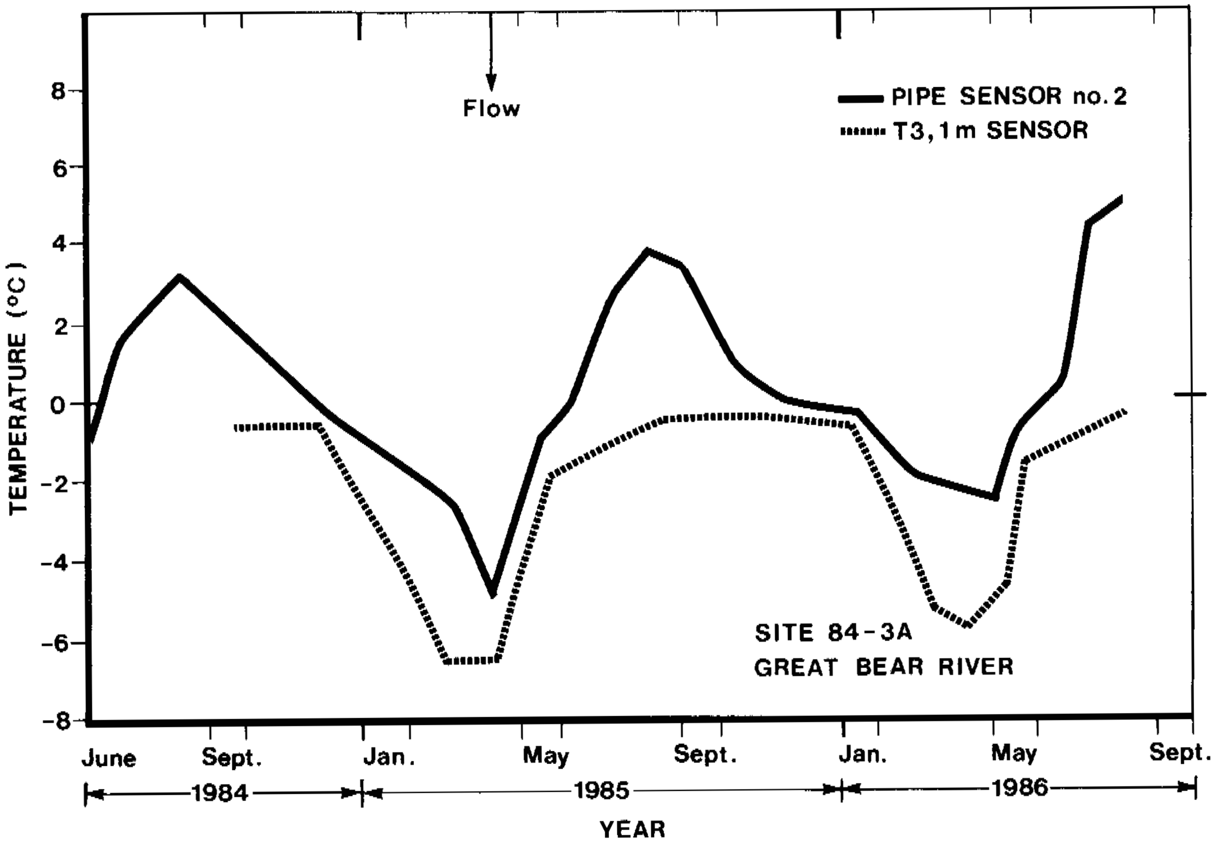

Flow
PIPE SENSOR no.2
T3,1m SENSOR
TEMPERATURE (°C)
8
6
4
2
0
-2
-4
-6
-8
SITE 84-2A
CANYON CREEK
June
Sept.
Jan.
May
Sept.
Jan.
May
Sept.
1984
1985
1986
YEAR

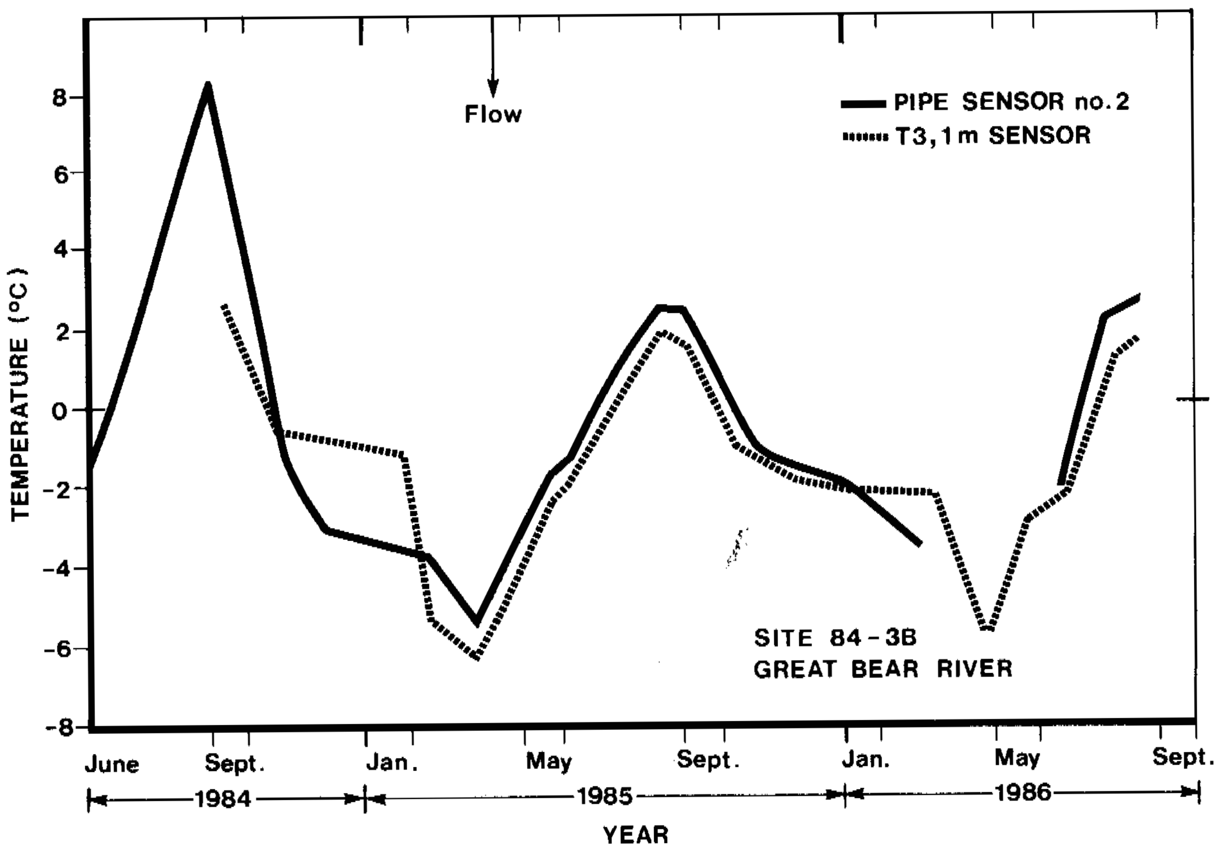


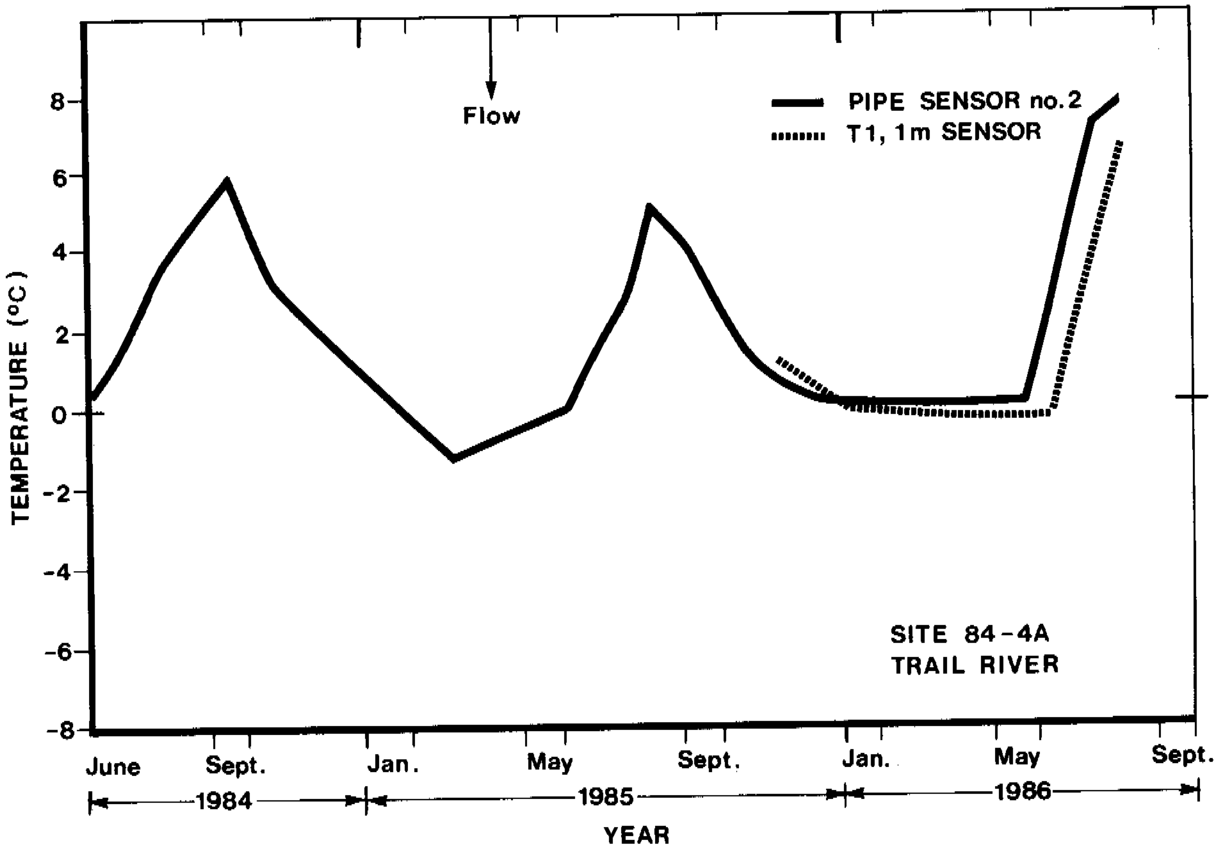
Flow
PIPE SENSOR no.2
T3,1m SENSOR
TEMPERATURE (°C)
8
6
4
2
0
-2
-4
-6
-8
SITE 84-2B
CANYON CREEK
June
Sept.
Jan.
May
Sept.
Jan.
May
Sept.
1984
1985
1986
YEAR

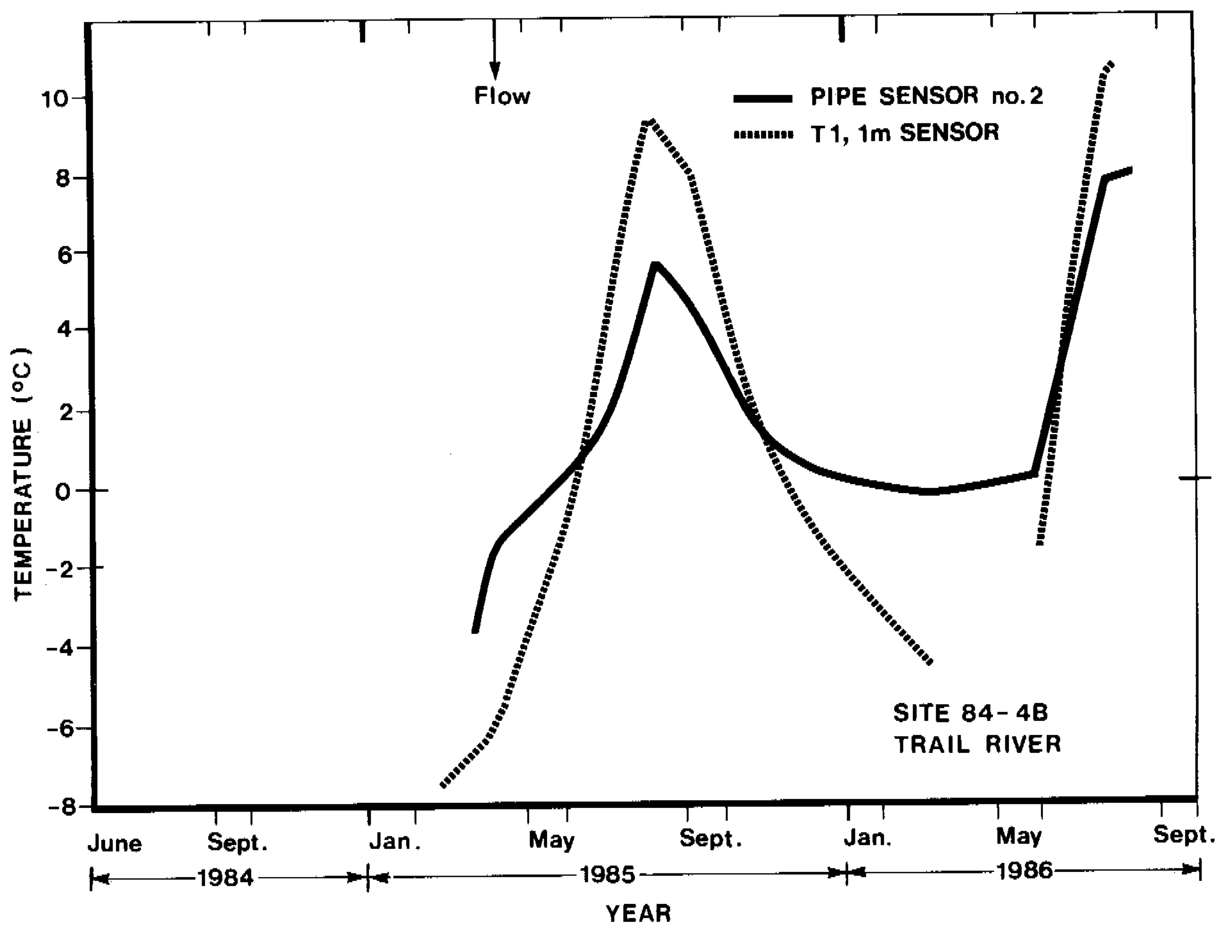


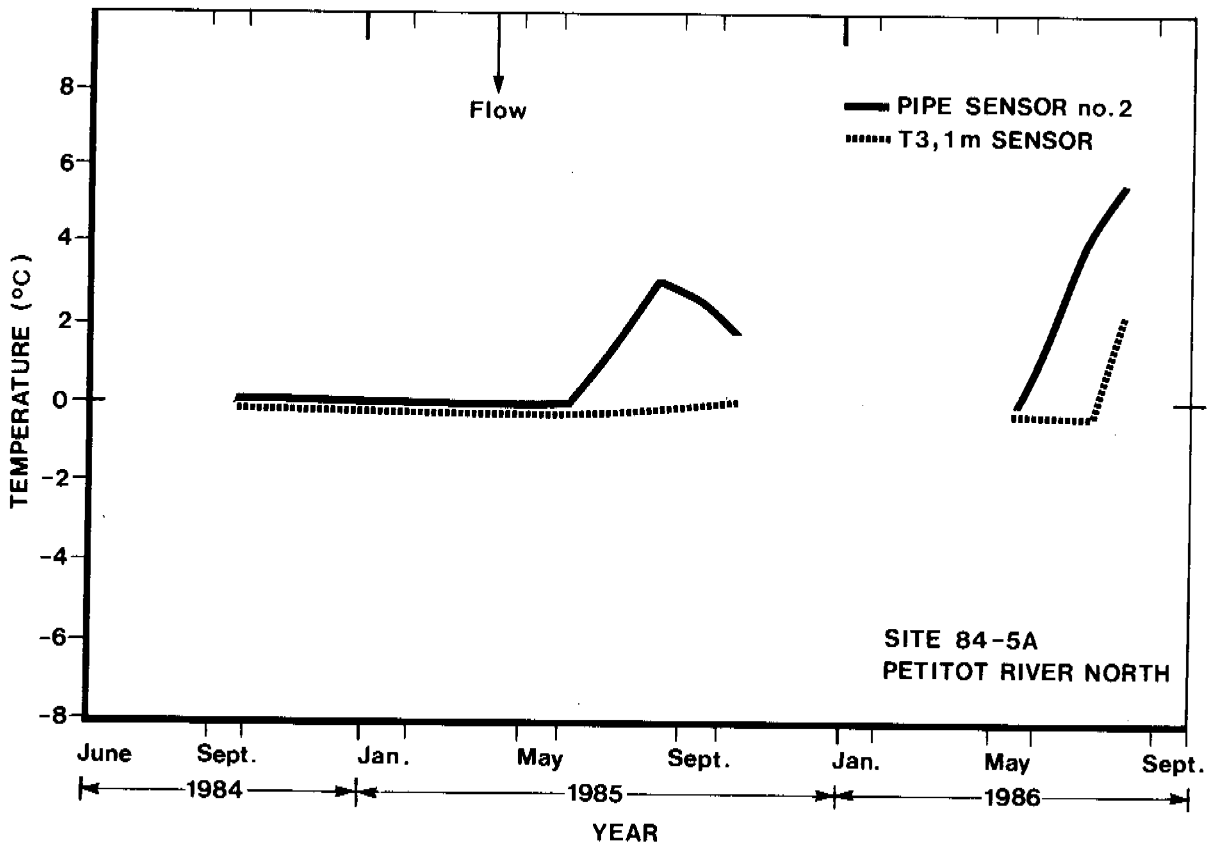
Flow
PIPE SENSOR no.2
T3, 1m SENSOR
TEMPERATURE (°C)
8
6
4
2
0
-2
-4
-6
-8
SITE 84-2C
CANYON CREEK
June
Sept.
Jan.
May
Sept.
Jan.
May
Sept.
1984
1985
1986
YEAR


PIPE SENSOR no. 2
T3, 1m SENSOR
Flow
SITE 84-3A
GREAT BEAR RIVER
TEMPERATURE (°C)
8
6
4
2
0
-2
-4
-6
-8
June
Sept.
Jan.
May
Sept.
Jan.
May
Sept.
1984
1985
1986
YEAR

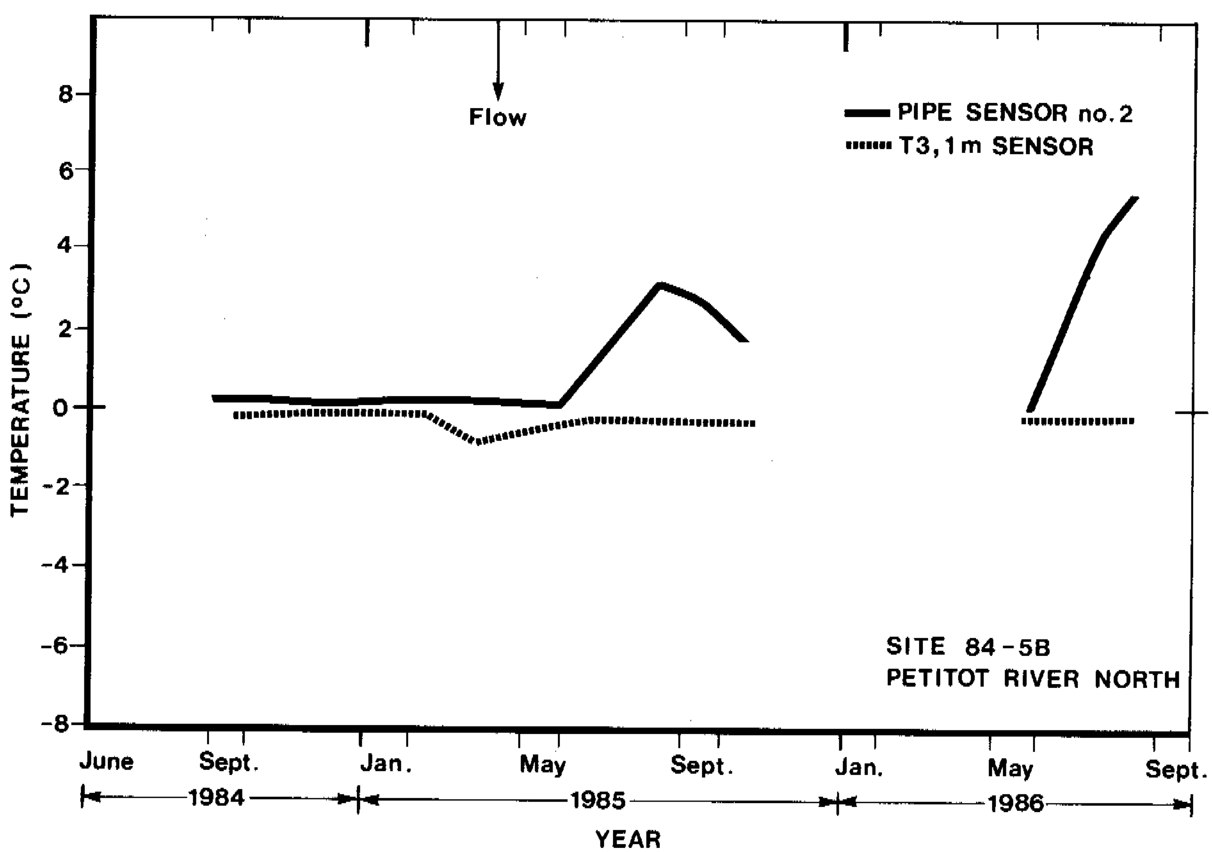

PIPE SENSOR no. 2
T3, 1m SENSOR
Flow
SITE 84-3B
GREAT BEAR RIVER
TEMPERATURE (°C)
8
6
4
2
0
-2
-4
-6
-8
June
Sept.
Jan.
May
Sept.
Jan.
May
Sept.
1984
1985
1986
YEAR


Flow
PIPE SENSOR no.2
T1, 1m SENSOR
SITE 84-4A
TRAIL RIVER
TEMPERATURE (°C)
8
6
4
2
0
-2
-4
-6
-8
June
Sept.
Jan.
May
Sept.
Jan.
May
Sept.
1984
1985
1986
YEAR

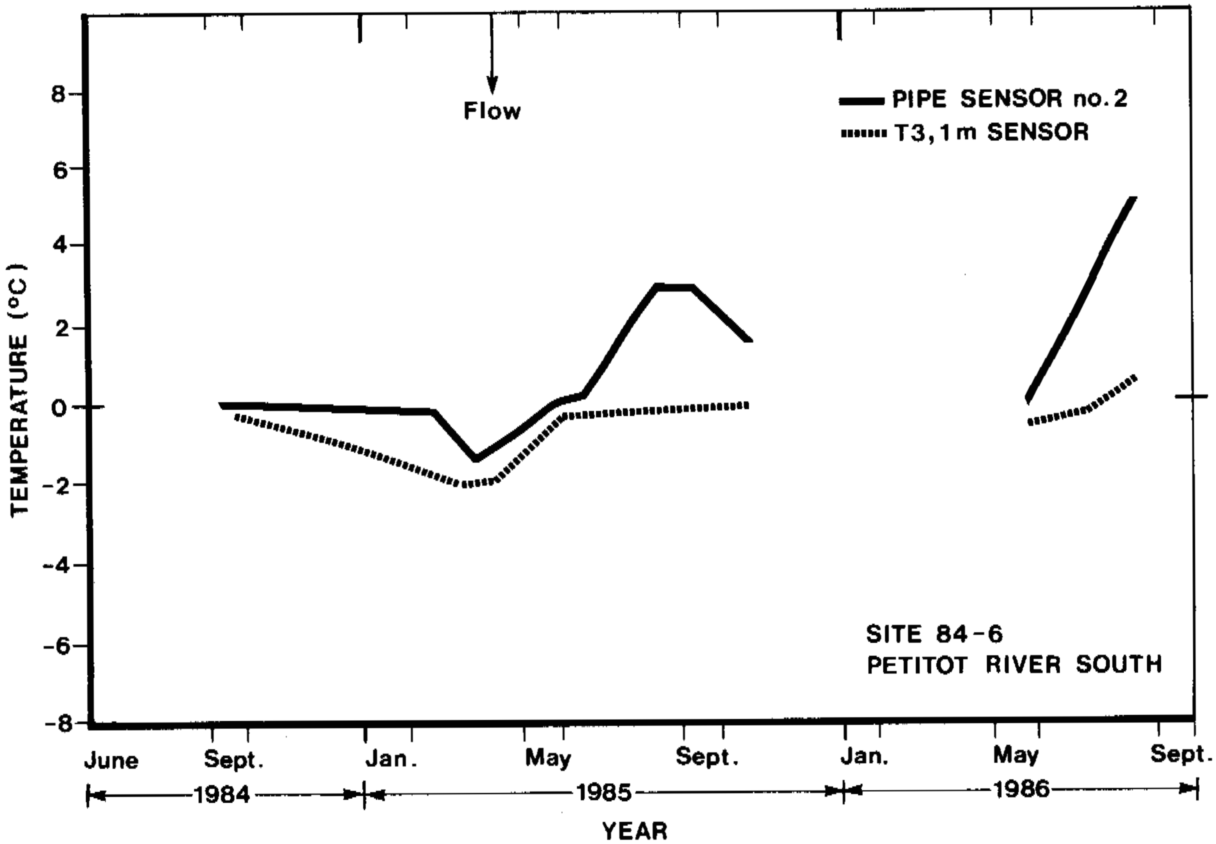

Flow
PIPE SENSOR no.2
T1, 1m SENSOR
SITE 84-4B
TRAIL RIVER
TEMPERATURE (°C)
10
8
6
4
2
0
-2
-4
-6
-8
June
Sept.
Jan.
May
Sept.
Jan.
May
Sept.
1984
1985
1986
YEAR

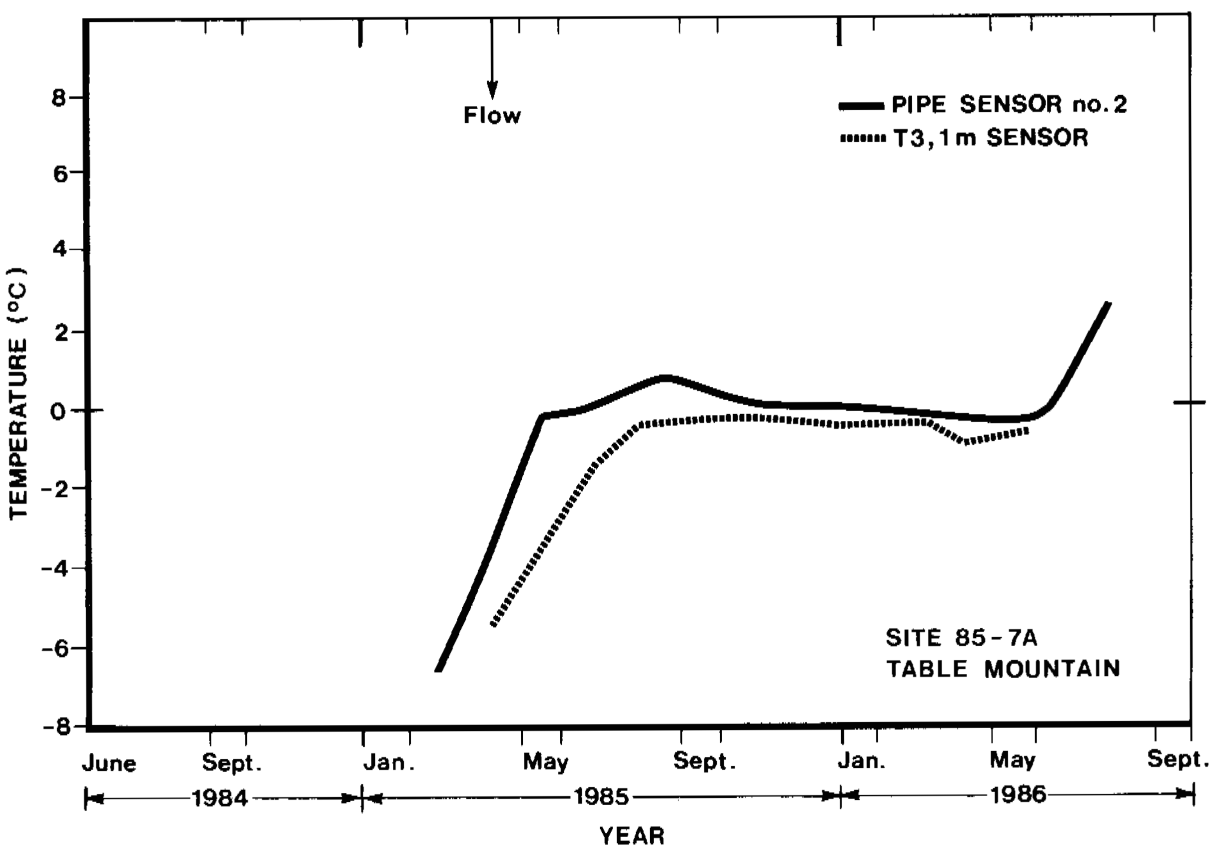


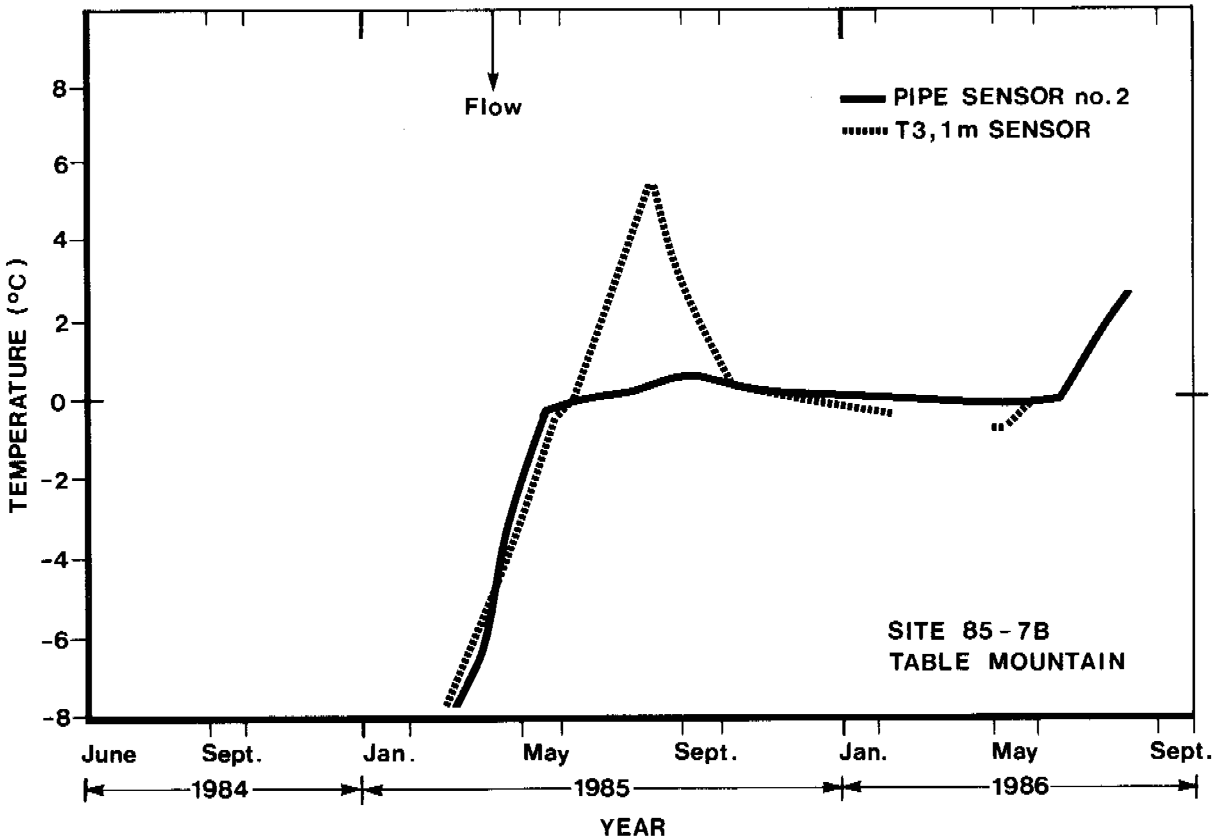
Flow
PIPE SENSOR no. 2
T3, 1 m SENSOR
TEMPERATURE (°C)
8
6
4
2
0
-2
-4
-6
-8
SITE 84-5A
PETITOT RIVER NORTH
June
Sept.
Jan.
May
Sept.
Jan.
May
Sept.
1984
1985
1986
YEAR

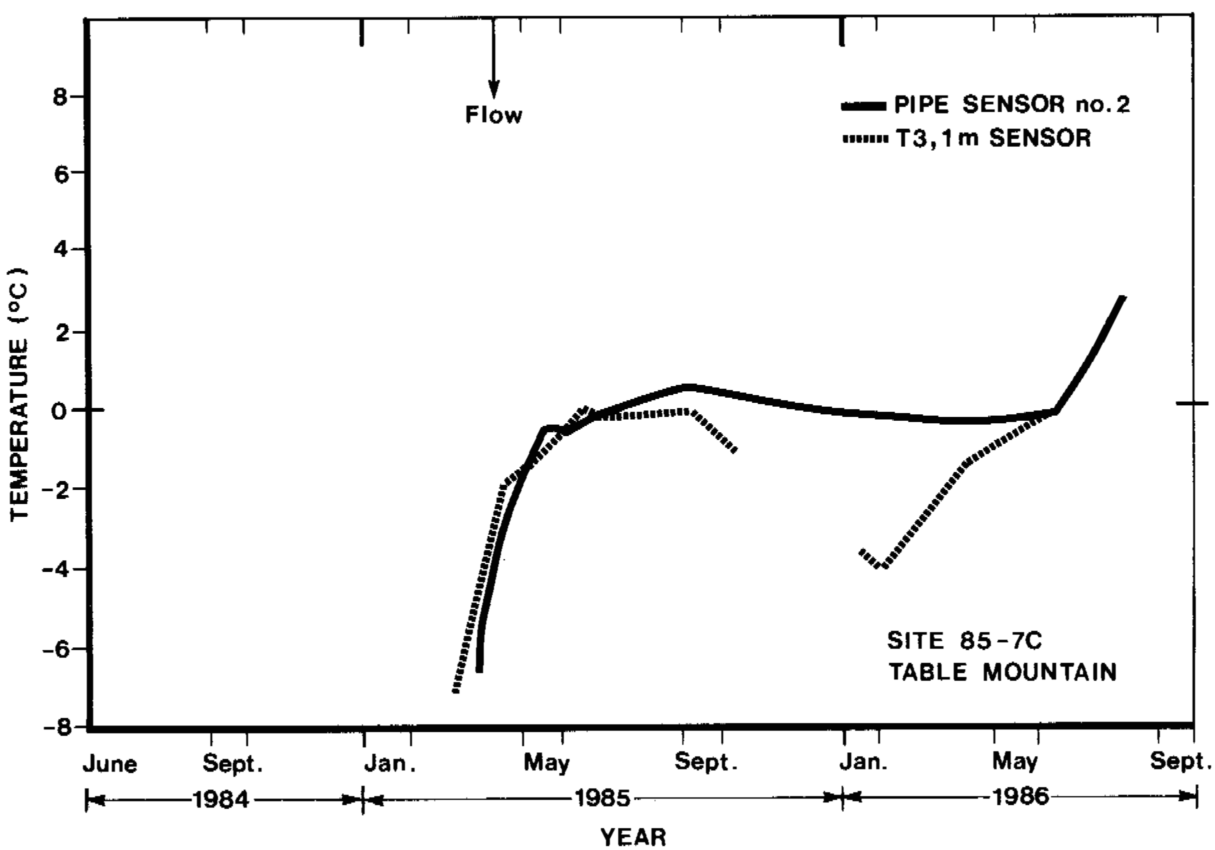


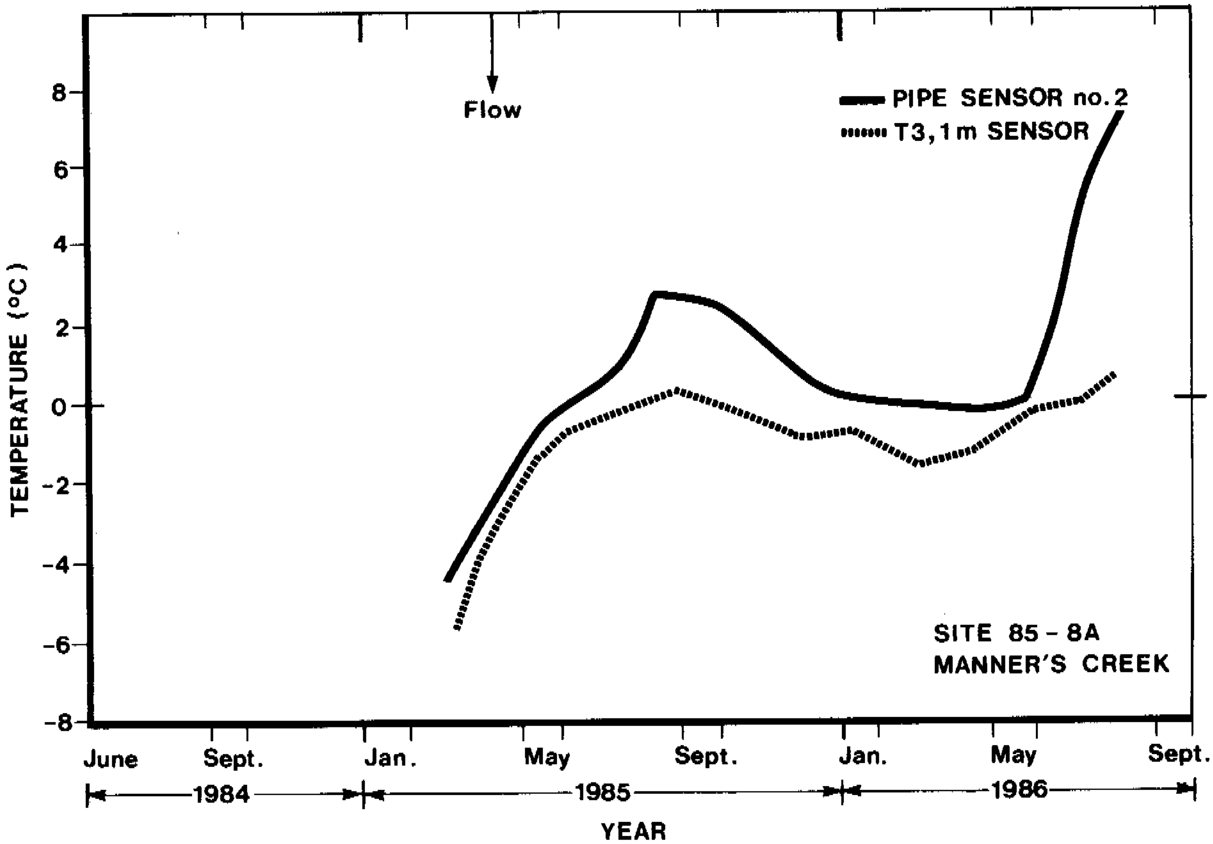
Flow
PIPE SENSOR no. 2
T3, 1 m SENSOR
TEMPERATURE (°C)
8
6
4
2
0
-2
-4
-6
-8
SITE 84-5B
PETITOT RIVER NORTH
June
Sept.
Jan.
May
Sept.
Jan.
May
Sept.
1984
1985
1986
YEAR

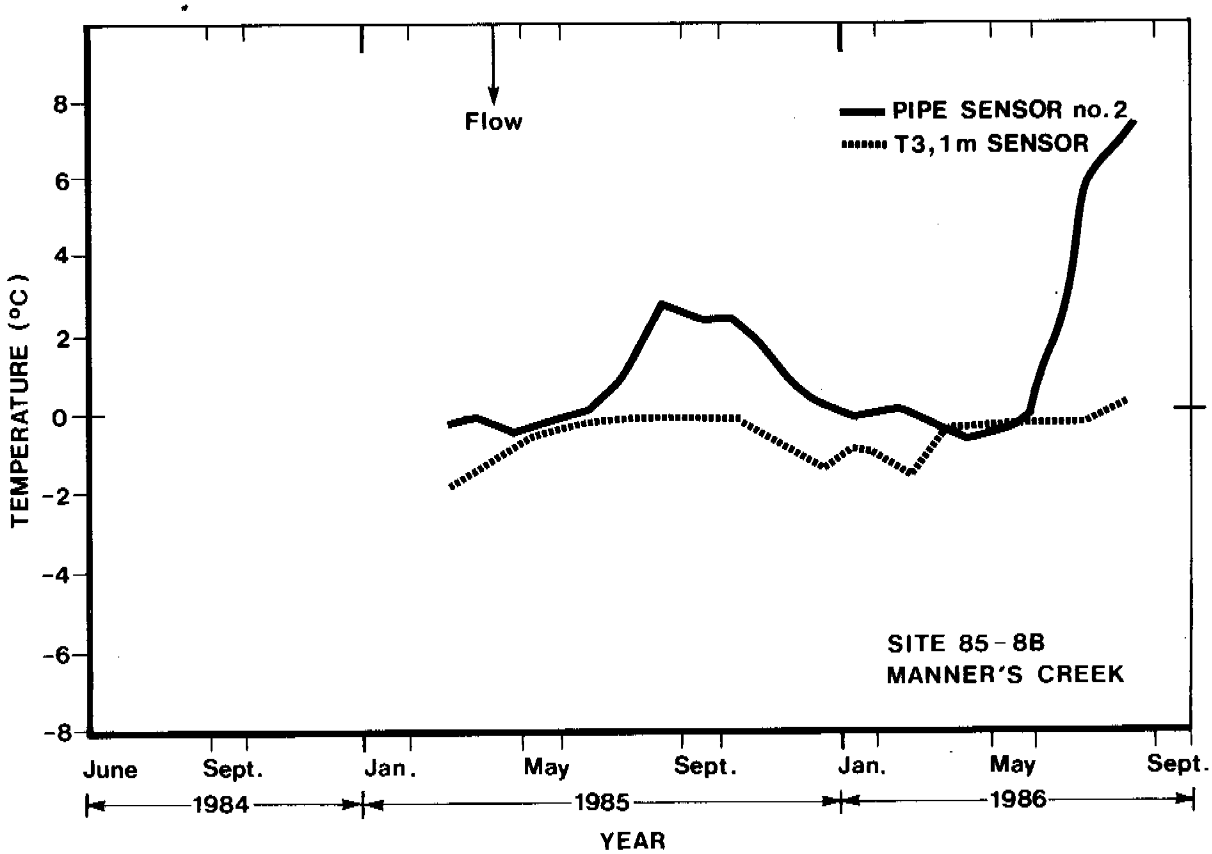

Flow
PIPE SENSOR no.2
T3, 1m SENSOR
TEMPERATURE (°C)
8
6
4
2
0
-2
-4
-6
-8
SITE 84-6
PETITOT RIVER SOUTH
June
Sept.
Jan.
May
Sept.
Jan.
May
Sept.
1984
1985
1986
YEAR

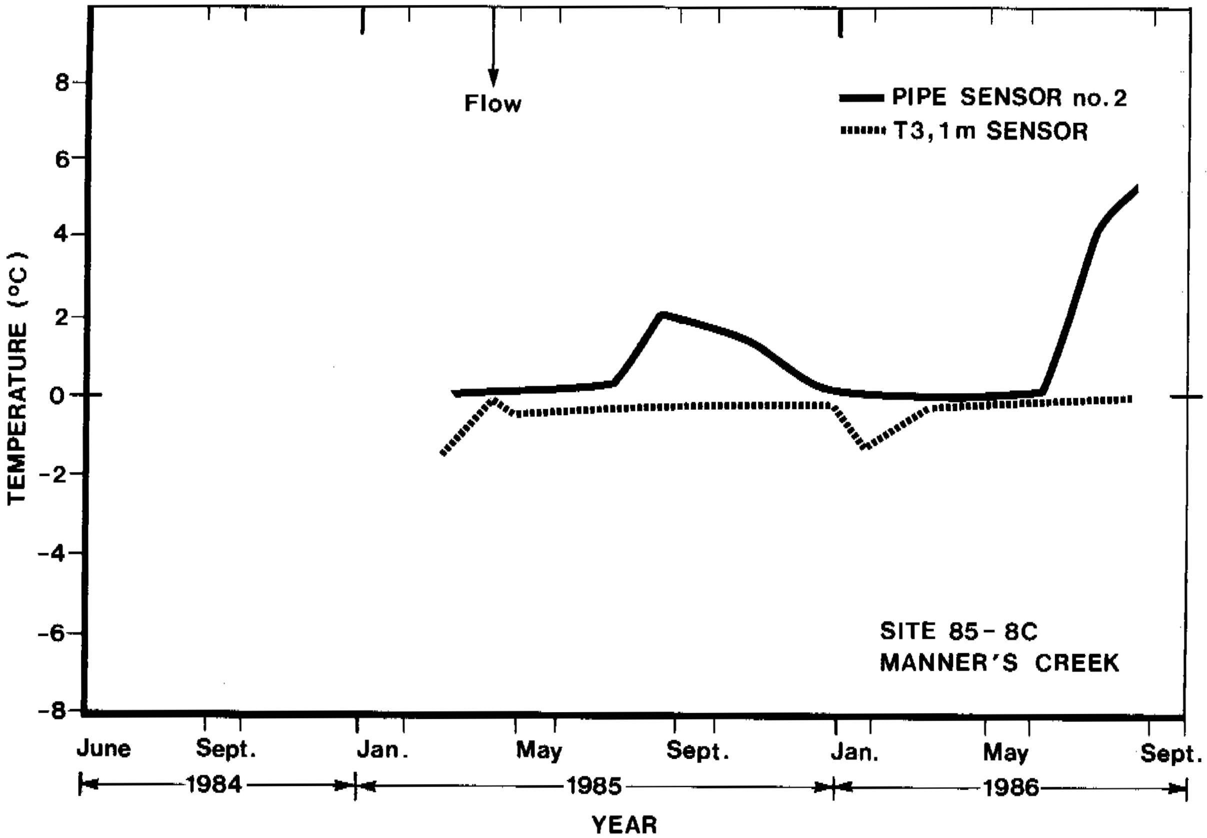

Flow
PIPE SENSOR no.2
T3, 1m SENSOR
TEMPERATURE (°C)
8
6
4
2
0
-2
-4
-6
-8
SITE 85-7A
TABLE MOUNTAIN
June
Sept.
Jan.
May
Sept.
Jan.
May
Sept.
1984
1985
1986
YEAR

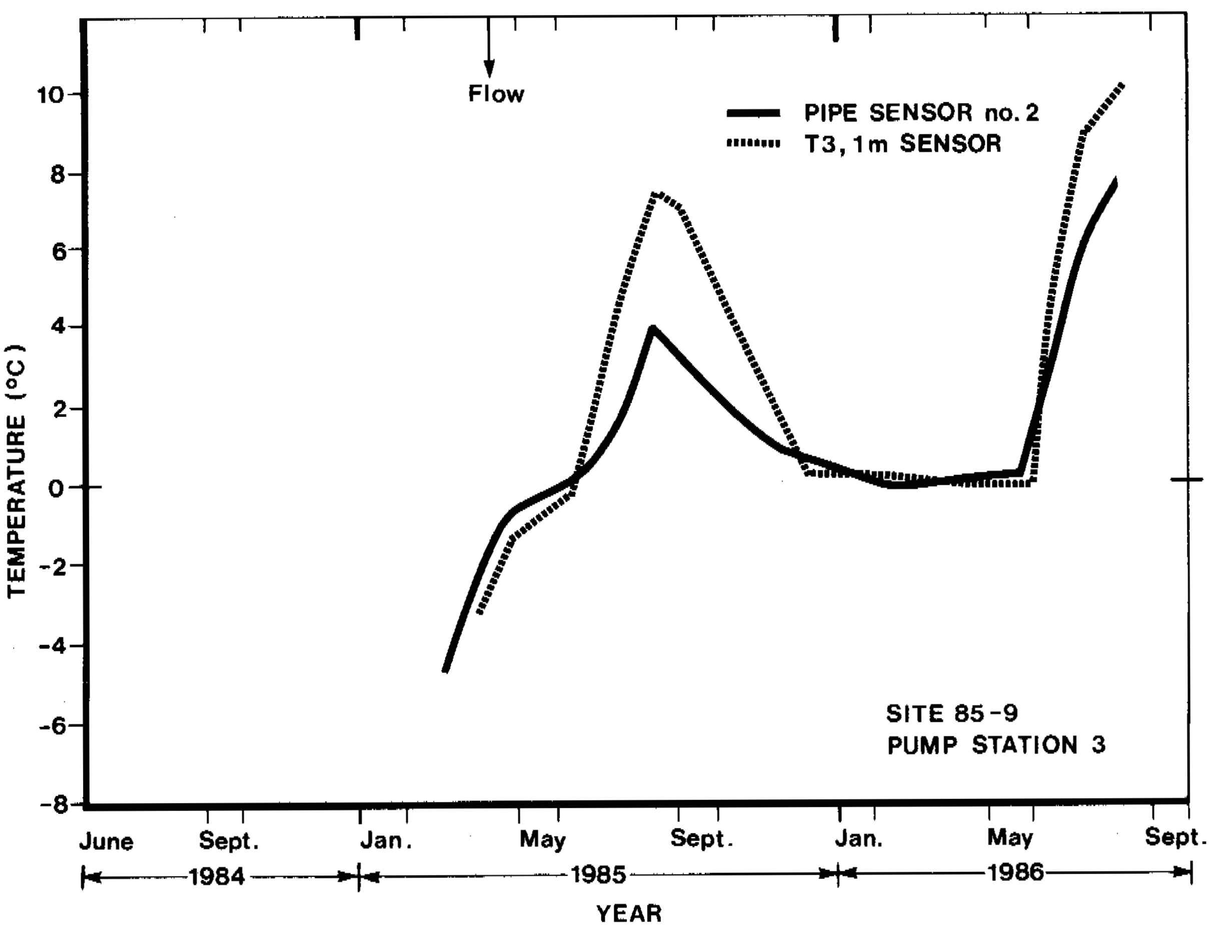

8
6
4
2
0
-2
-4
-6
-8
TEMPERATURE (°C)
Flow
PIPE SENSOR no. 2
T3, 1 m SENSOR
SITE 85-7B
TABLE MOUNTAIN
June
Sept.
Jan.
May
Sept.
Jan.
May
Sept.
1984
1985
1986
YEAR

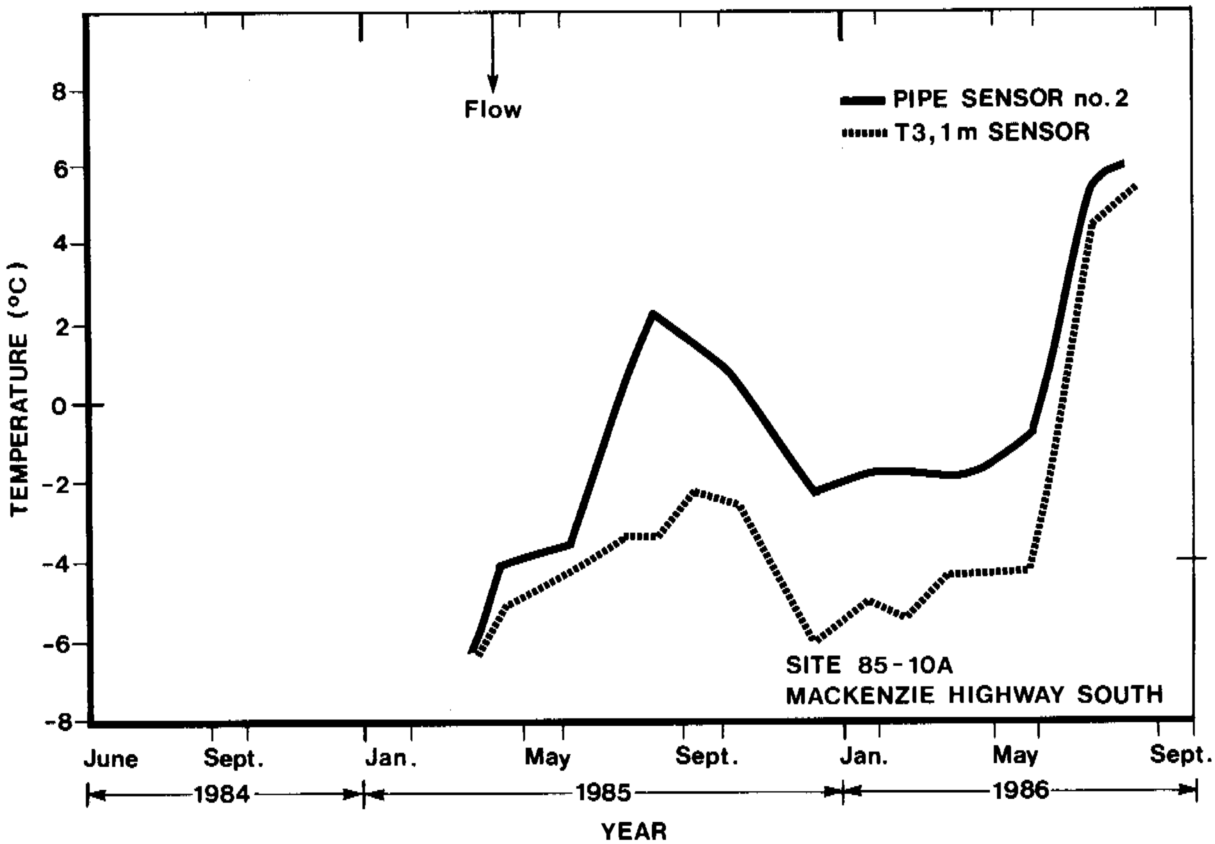

8
6
4
2
0
-2
-4
-6
-8
TEMPERATURE (°C)
Flow
PIPE SENSOR no. 2
T3, 1 m SENSOR
SITE 85-7C
TABLE MOUNTAIN
June
Sept.
Jan.
May
Sept.
Jan.
May
Sept.
1984
1985
1986
YEAR

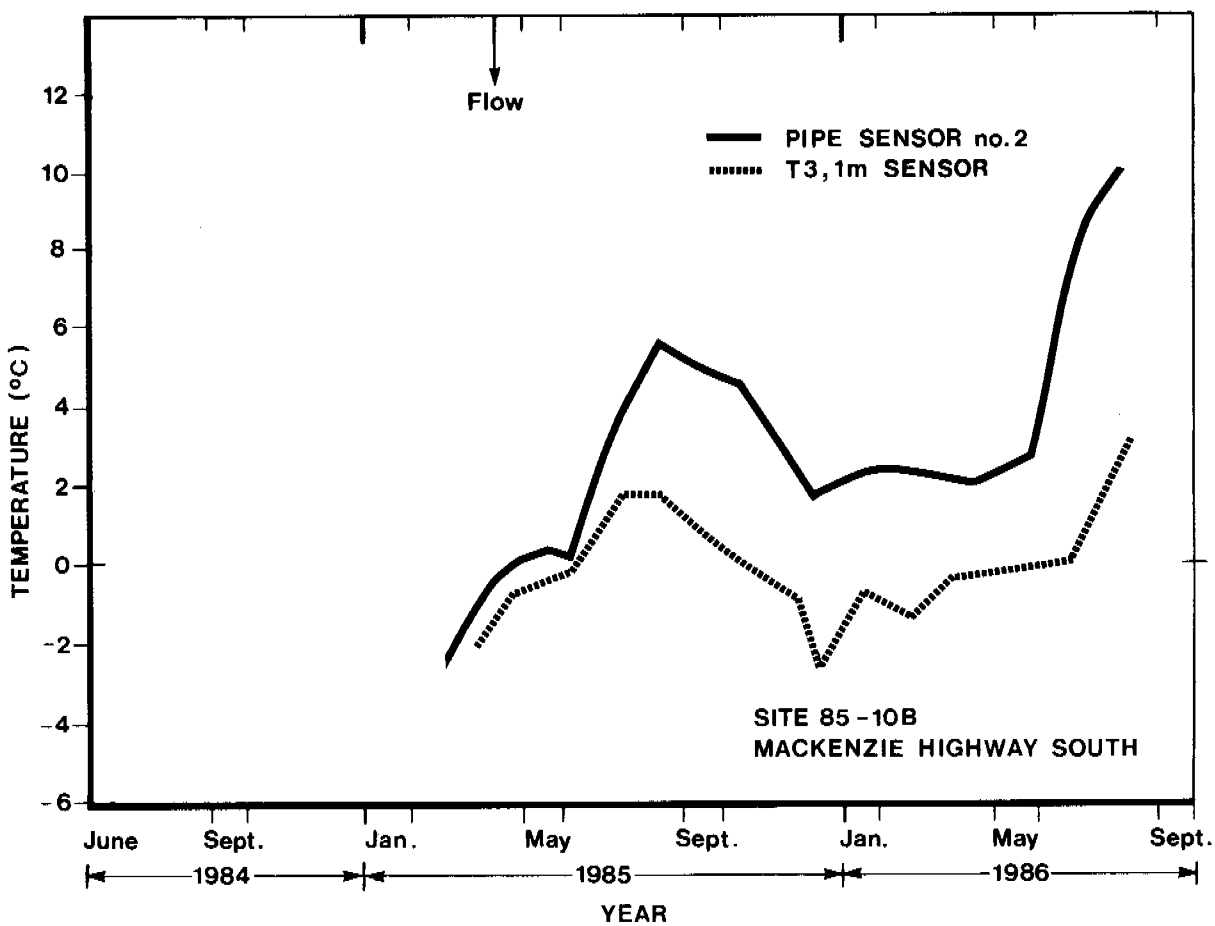

Flow
PIPE SENSOR no. 2
T3, 1 m SENSOR
SITE 85 - 8A
MANNER'S CREEK
TEMPERATURE (°C)
8
6
4
2
0
-2
-4
-6
-8
June
Sept.
Jan.
May
Sept.
Jan.
May
Sept.
1984
1985
1986
YEAR

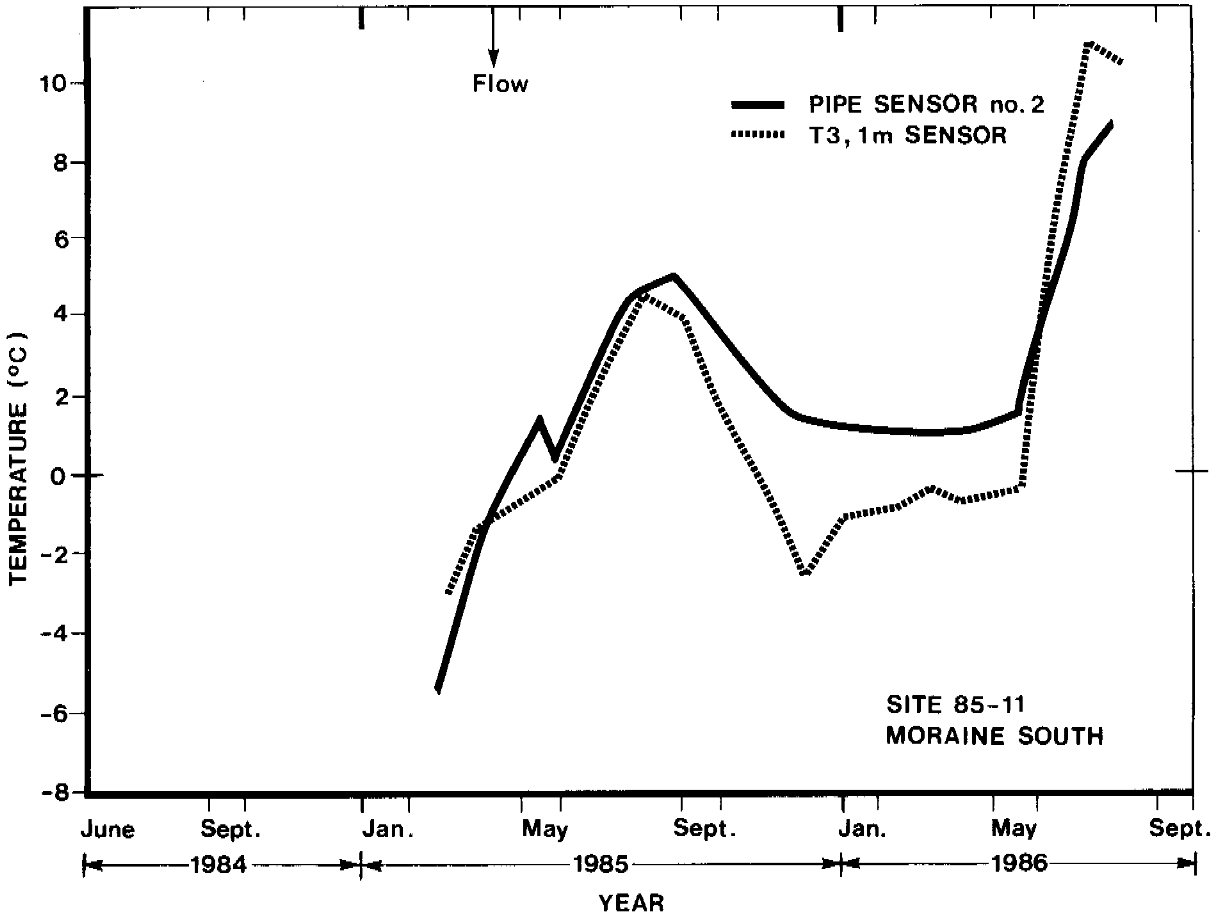

Flow
PIPE SENSOR no. 2
T3, 1 m SENSOR
SITE 85 - 8B
MANNER'S CREEK
TEMPERATURE (°C)
8
6
4
2
0
-2
-4
-6
-8
June
Sept.
Jan.
May
Sept.
Jan.
May
Sept.
1984
1985
1986
YEAR


Flow
PIPE SENSOR no. 2
T3, 1m SENSOR
TEMPERATURE (°C)
8
6
4
2
0
-2
-4
-6
-8
SITE 85-8C
MANNER'S CREEK
June
Sept.
Jan.
May
Sept.
Jan.
May
Sept.
1984
1985
1986
YEAR

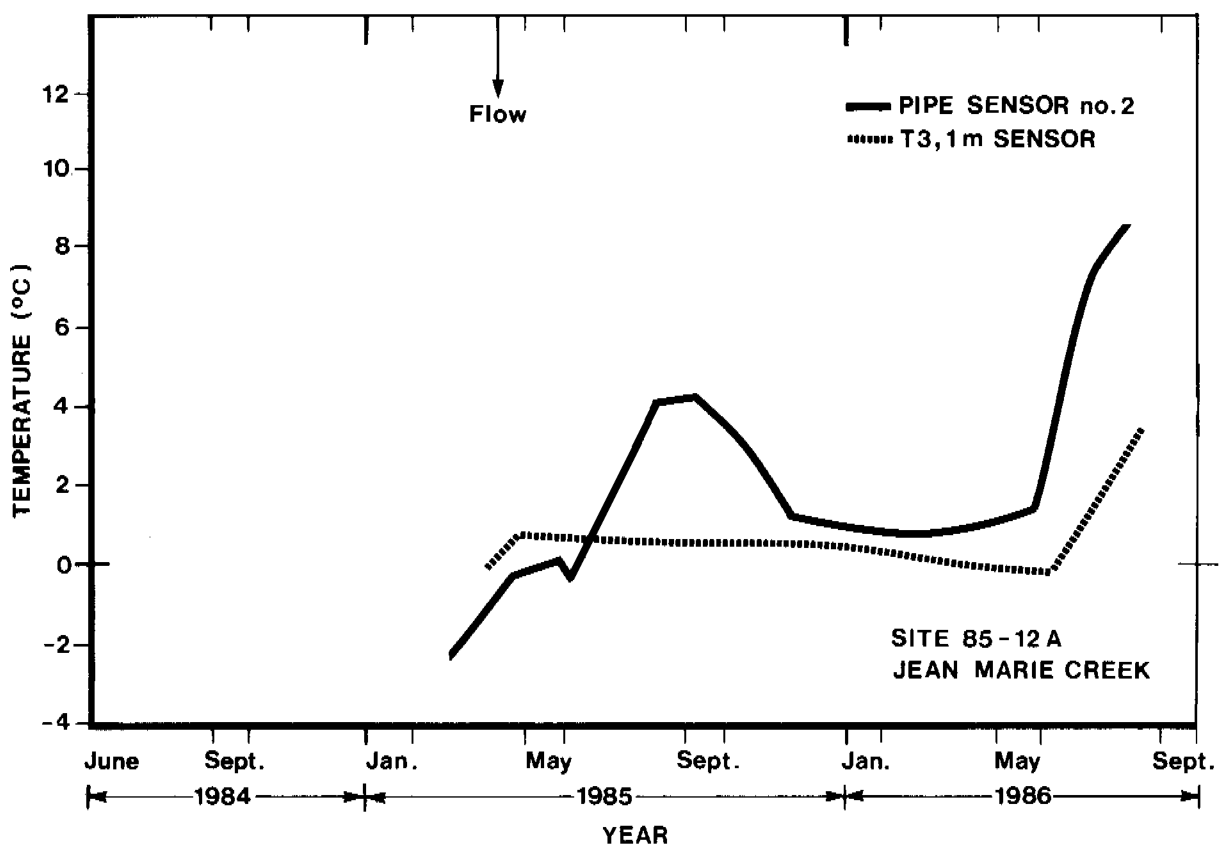

Flow
PIPE SENSOR no. 2
T3, 1m SENSOR
TEMPERATURE (°C)
10
8
6
4
2
0
-2
-4
-6
-8
SITE 85-9
PUMP STATION 3
June
Sept.
Jan.
May
Sept.
Jan.
May
Sept.
1984
1985
1986
YEAR


Flow
PIPE SENSOR no. 2
T3, 1m SENSOR
TEMPERATURE (°C)
8
6
4
2
0
-2
-4
-6
-8
SITE 85-10A
MACKENZIE HIGHWAY SOUTH
June
Sept.
Jan.
May
Sept.
Jan.
May
Sept.
1984
1985
1986
YEAR

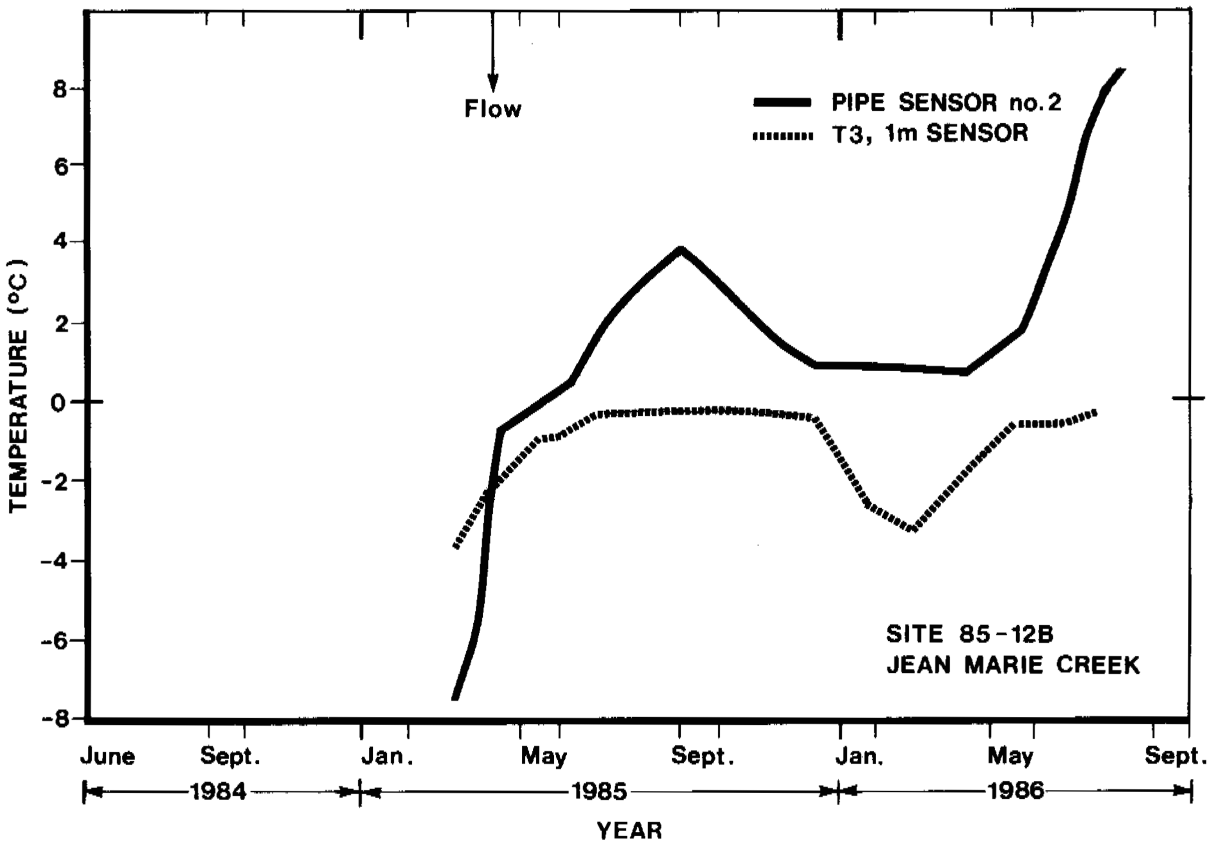

Flow
PIPE SENSOR no. 2
T3, 1m SENSOR
TEMPERATURE (°C)
12
10
8
6
4
2
0
-2
-4
-6
SITE 85-10B
MACKENZIE HIGHWAY SOUTH
June
Sept.
Jan.
May
Sept.
Jan.
May
Sept.
1984
1985
1986
YEAR



Flow
PIPE SENSOR no. 2
T3, 1m SENSOR
TEMPERATURE (°C)
10
8
6
4
2
0
-2
-4
-6
-8
SITE 85-11
MORAINE SOUTH
June
Sept.
Jan.
May
Sept.
Jan.
May
Sept.
1984
1985
1986
YEAR



Flow
PIPE SENSOR no. 2
T3, 1m SENSOR
TEMPERATURE (°C)
12
10
8
6
4
2
0
-2
-4
SITE 85-12 A
JEAN MARIE CREEK
June
Sept.
Jan.
May
Sept.
Jan.
May
Sept.
1984
1985
1986
YEAR



Flow
PIPE SENSOR no.2
T3, 1m SENSOR
TEMPERATURE (°C)
8
6
4
2
0
-2
-4
-6
-8
SITE 85-12B
JEAN MARIE CREEK
June
Sept.
Jan.
May
Sept.
Jan.
May
Sept.
1984
1985
1986
YEAR

APPENDIX D

REPORTS BASED ON THE NORMAN WELLS PIPELINE PERMAFROST AND TERRAIN RESEARCH AND MONITORING PROGRAM

REPORTS BASED ON THE NORMAN WELLS PIPELINE PERMAFROST AND TERRAIN RESEARCH AND MONITORING PROGRAM

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