17450
V. 5

FOSTER RESEARCH
Suite 200, Notre Dame Place, 255 - 17 Avenue S.W.
Calgary, Alberta T2S 2T8 (403) 228-0822
Telecopier #: (403) 228-3953

January 21, 1988
File: 1436-5

BY COURIER

Mr. Zhou Bingyuan
Economist Engineer, Planning Department
Ministry of Petroleum Industry
The People's Republic of China
Deshengmenwai Liupukang
BEIJING, CHINA

Dear Mr. Zhou:

Enclosed is Paper 12, "Planning and Managing a Major Pipeline in a Remote and High Cost Area" for MOPI translation and internal distribution for the March 21, 1988 conference. Mr. Pearce's biography is also enclosed.

Also enclosed is additional information, papers, and a bibliography on the Norman Wells project for your information and use as you see fit.

Sincerely,

Ted Best

E. W. Best

EWB/pj
Enclosure

cc: Ms. S. Shum
The World Bank
J. B. Ridsdel
Petro-Canada International
Assistance Corporation

William M. Pearce, Vice-President, Special Project
Interprovincial Pipe Line Ltd.
10201 - Jasper Avenue
Edmonton, Alberta
T5J 2J9

Telephone 420-5201

Mr. Pearce has been engaged in crude oil pipeline work for the last 30 years primarily in the engineering and management fields.

He was born and studied in England principally the Central Technical College, Burmingham and specialized in electrical power engineering.

He came to Canada in 1953 and is a registered Professional Engineer in Ontario and Alberta.

After working in the power generation field, he joined IPL in 1957, as a pump station design engineer and continued work in the changeover from diesel to electric equipment.

With increasing responsibilities he was appointed Manager of the Company's engineering dept. in 1978 and the next year was appointed Project Manager of the Norman Wells Pipeline group.

He managed the project from its initial to operational stage in 1985 and later set up the Special Projects group to plan further frontier pipelines for both oil and gas together with a proposal to transport water in Canada using high pressure oil pipeline techniques.

WORLD BANK CHINA CONFERENCE

MARCH 1988

PLANNING AND MANAGING A MAJOR PIPELINE IN A REMOTE AND HIGH COST AREA

Introduction

This paper describes actual work on the Norman Wells pipeline which was constructed by Interprovincial Pipe Line Limited from 1982 to 1985. Much of the engineering detail, particularly the technical problems of working in permafrost are not discussed, in order to focus on management issues, particularly project administration and cost control.

Interprovincial is the largest crude oil pipeline system in North America with approximately 11,000 km of lines.

Engineering and environmental papers have been previously written and are referenced in this paper (with copies available).

To better understand the challenges in building Canada's first major oil line connecting the North with Southern markets, some time has been given to describing the historical, geographic and political background.

General Information

Geographical

Most of the oil and gas in Canada has been found in the western sedimentary basin principally in the Province of Alberta, but the potential for oil and gas continues northward into the Northwest Territories and significant finds of both oil and gas have been made in the Beaufort Sea and the High Arctic. The most accessible discoveries have been made in the delta of the Mackenzie River and within the continental shelf.

The Northwest Territories of Canada consists of approximately 3.4 million square kilometers with a population of only 52 thousand (See Fig. 1). The principal access is along the Mackenzie River Valley and there are very few roads in the Valley except during the winter. Most native people have moved into small settlements along the river and major transportation is by river barge and air. The mean annual temperature at Norman Wells is $-6^{\circ}C$ and in December there is only about 3 hours of daylight.

Historical

In 1921 Imperial Oil Limited conducted a drilling program which resulted in a significant discovery of oil at Norman Wells. The oil field extended under the present course of the Mackenzie River and following that discovery, a few wells were drilled on the shore and from islands in the river with the oil being processed through a small local distillation plant. Esso Resources Canada Limited is a subsidiary of Imperial Oil Limited and now operates the oil field.

This small production continued until 1979, when Esso planned to introduce a secondary recovery program using water injection and a major drilling program which would increase the production from 450 cubic meters per day to 4500 cubic meters per day. With the river being frozen for about 6 months of the year, barging the oil to market would require huge storage tanks and the only reasonable alternative was a 324 mm buried pipeline.

Following long negotiations, Esso Resources agreed that Interprovincial should apply to government agencies for the necessary permits to construct a pipeline from Norman Wells to Northwest Alberta to move Esso's increased production. The agreement contained clauses pertaining to capital, operating costs, and tariff structure to satisfy Esso that the line would be built at minimum cost and in time to meet the oil field development program which also required considerable government approvals.

In southern Canada, oil and gas pipelines have been constructed for over 100 years and with this experience, construction practices are conventional except perhaps in very wet or swampy areas where heavy equipment cannot be supported and work is then carried out in the winter when the ground is frozen. In the North, winter work is essential and this pipeline was seen as a "pilot project" for larger projects in the 1990's.

Regulatory

In Canada the National Energy Board is an agency of the federal government responsible for the movement of oil and gas either across provincial or international borders. The Board has overall legal authority and has the power to call public hearings, approve or disapprove proposed projects, and make rulings on the proposed tariffs of oil and gas pipelines.

In Northern Canada the use of most land is controlled by the Federal Government through its Department of Indian Affairs and Northern Development. Application was made for a strip of land 30 metres wide on which to build the pipeline and this resulted in a second public review process focusing on environmental and social issues. The Provincial government of Alberta has an established process for pipeline construction and followed the recommendation of the National Energy Board.

The project required many applications to other levels of government and the public hearings were attended by all interested public groups. The major opponents to the oil field development and pipeline were environmental groups who were concerned with the impact of construction, and the native people who claimed that the land and its resources belonged to them.

The applications and public hearings took 1 1/2 years and although the project was approved, it was subjected to a further two year delay to allow native people time to become better prepared, and to allow completion of many environmental and socio-economic conditions imposed on the pipeline company. The complex regulatory system required special attention throughout the life of the project.

Appendix 1 shows the list of additional studies that were required during the two year delay. On completion, these studies were forwarded to each of the public interest groups for their review following which the National Energy Board approved or disapproved the study. It will be noted that these studies covered a wide range of subjects and the process created a precedent in Canadian regulatory history.

Political

Until recently there has been no formal agreement between the native people of the Northwest Territories and the Canadian Government so that ownership of the land and its resources has been subject to considerable political dispute. Over the past few years, the concern for the northern environment in Canada has resulted in a series of land use regulations which must be followed on any construction project, and these are supported by public hearing processes where anyone may voice their concerns prior to the start of major work.

This concludes the background of the project which I have included to show that in Canada, major projects particularly in remote areas present unique management problems in addition to normal industrial issues. We will now consider the resulting management processes starting with the preliminary approvals in 1981 and finishing when oil flowed through the line in 1985.

The Pipeline Project

The objectives of the pipeline company could be simply stated as follows:

"To design, construct and operate a crude oil pipeline with the lowest capital and operating costs and in accordance with approved environmental practices. To maximize the amount of socio-economic benefits to the northern region and native people, and to complete the work in a restricted timetable".

Pipeline projects of this size and complexity require some 1400 construction people during the 3 month peak period with a peak staff of about 350 design, supervisory and management persons.

As shown on Fig. 2, the distance from Norman Wells to Zama which is the closest connection to a pipeline in Alberta is 874 kilometers. The route crosses large areas of muskeg which are impassable except in winter. There would be two major river crossings, the Great Bear and the Mackenzie River with 140 smaller stream crossings. Intermittent permafrost is found over almost the entire route. Three pump stations and several maintenance bases had to be built. Approximately 50% of the length of the pipeline would run through permafrost most of which is concentrated at the north end (Fig. 3).

Project Management

Pipeline companies in Canada do not have sufficient permanent staff to undertake all aspects of such a large construction project and it was decided at an early date that the Interprovincial staff team would be kept small and provided with sufficient authority to allow fast decisions to be made on all aspects of the work. This team of only six managers and about ten immediate staff supervised the work of two contract management groups (See Fig. 4). This practice was unique as in Canada companies generally recruit larger staffs for projects of this size.

The success of the Interprovincial approach was due to the selection process used to choose consulting staff and the careful description of their responsibilities.

The Company management team directly operated the Northern Public Relations policies and the Northern Development policies which identified and encouraged business opportunities in Northern communities and employment of northerners. All other work was divided into two management groups.

Technical Services Group

The principal responsibilities of this group are listed below:

Engineering Design - Pipeline

Engineering Design - Facilities

Engineering Design - Communications

Materials and Installation Specifications

Land

Surveys

Purchasing

Environment

Geotechnical

Hydrological

Quality Assurance

The group was made up of six companies working in their specialized field and at its peak the staff total was about 100 people. The Engineering and Technical problems connected with the Norman Wells pipeline have been previously published and these are listed in the bibliography.

Construction Services Management Group

This large group using the designs and specifications of the Technical group carried out the process of contract award, logistics and construction supervision. Their total responsibilities were as follows:

- Detailed Construction Plan
- Construction Schedule
- Construction Logistics
- Construction Contract Documents
- Invitation to Tender
- Contract Awards
- Contract Administration
- Construction Cost Estimate
- Construction Manpower Plan

Overall Project Schedule

Overall Project Cost Control

Project Monthly Progress Report

Materials Expediting

Construction Inspection

Staging Areas and Camp Management

Hydrostatic Testing Program

Commissioning and Project Start Up

Construction Approvals Process

This group operated both in the South and on the pipeline location with a peak staff of about 250.

Selection Process

The award of consulting, management or technical contracts is not necessarily made to the lowest bidder. On Northern work, particularly pipelines, it is impossible to quote a fixed total price for services which would be acceptable to the pipeline company. Prices are generally quoted on a unit price basis of "man-hours; or "man days" together with a multiplier which would apply to overhead costs and profit. A multiplier would range from 1.8 to 2.5, depending on the scope of the work.

The selection process for Management and Technical Support Services was generally as follows:

- A number of suitable consulting companies were identified and invited to bid;
- The project was described in general terms and the bidders were required to provide their own estimate of total personnel requirements and total man-hours;
- Costs were quoted as hourly wages for each classification together with a multiplier which would provide for overhead costs and profit.
- Related previous experience was required together with the personal experience of their senior staff.

The evaluation of these bids consisted of two parts, the quantitative part which considers the validity of estimated man-hours and their associated unit costs and the qualitative part which is more difficult to analyze and translate into a measurable value. A company selection team compiled a list of all the desirable qualities that would be expected from a support group working on the actual project. The individual qualities were given a value in relation to other qualities which reflected their importance to the success of the project.

The main qualities that were considered in the above review are as follows and were adjusted to suit the particular work being considered:

- Previous experience on similar projects;
- Corporate resources, Canadian content in personnel and technology;
- General acceptability of proposed organization;
- Present workload or availability;
- Knowledge of project;
- Quality of senior personnel;
- Administration capability;
- Logistics planning capability;
- Estimating capability;
- Quality control capability;
- Cost control methodology;
- Contract production and administration;
- Supervision and inspection;
- Labor relation capability;
- Knowledge of special Northern requirements;
- Safety management;
- Knowledge of terms and conditions imposed by government regulators;
- Understanding of Northern political issues.

The selection teams then reviewed all the proposals and estimated the expected performance of each bidder in each of the quality areas. The final two or three companies were then interviewed for additional assessment. The estimated values of the various qualities and the estimated performance of each bidder were combined to provide an overall measure of potential success. This provided the best method of determining the most suitable group to provide the needed support for Interprovincial.

In this type work work where costs are not fixed but based on man-hours and unit costs, emphasis should be placed on the unit costs rather than the estimated total. The work is then managed to minimize the total hours expended.

For all subsequent work the contracts were administered by the Construction Services Management group, the most important of which was the actual pipeline construction.

Purchasing

On this project, senior management devoted considerable effort to develop most of the business strategies which would lower the cost of both materials and construction. Generally this was achieved by using market competition within the terms and conditions stated by government agencies. In addition it was possible to take advantage of a manufacturer's knowledge in other areas such as transportation and this was achieved by selection of the delivery location.

The general purchasing principles were as follows:

1. Maximize market competition
2. Maximize Canadian content
3. Require a satisfactory production control system
4. Establish quality assurance procedures and data recording.
5. Design specific strategies for each major purchase to minimize cost.

Two examples will be quoted, the first for the supply of all the main line pipe and secondly to plastic coat and transport the pipe.

Enquiries for pipe were sent to Canadian mills and also to certain Japanese mills. This resulted in a Canadian mill being the most competitive and increased the Canadian content of the pipeline. Cost savings were about 35%. The three factories who bid on the polyethylene coating of the pipe were deliberately not told where the pipe would be made and were required as part of their bid to transport the entire shipment by road, rail and barge to the stockpile locations in the North. In addition any damage to the pipe or coating would have to be repaired and payment would not be made until the material was delivered

in acceptable condition. This resulted in lower costs than the original estimate and at the same time ensured that the pipe would arrive in good condition. The cost savings were approximately 30%.

Transportation and Logistics

Fig. 2 shows that a highway and a railroad connects Alberta to the lake and river system in the Northwest Territories. From the town of Hay River a barge system operates to the Arctic Ocean and road transport can be used to the Town of Fort Simpson.

Before construction crews can be moved north, living quarters, equipment and fuel must be in place and the scheduling of these shipments became a major factor in planning of the pipeline. In late winter and early spring, truck loads must be reduced to avoid breaking the road surface, the barge system only operates for only about six months and air transport is subject to weather conditions.

Stockpile sites along the river were carefully chosen, and supplies were unloaded by barge during the summer preceeding the first winter of main line construction. Along the pipeline three 450 man prefabricated camps were set up, several pipe stockpiles and three main equipment areas.

Additional supplies were hauled by winter road after the ground was frozen and personnel were flown in, using small airstrips and the main airport at Norman Wells.

When the work was completed it was necessary to move all equipment and supplies to a river location or southwards along the winter road so it would not be trapped in the North for another season.

The transportation and logistics planning was a success and there were no major holdups due to lack of supplies.

Construction Planning

Fig. 5 shows the construction timetable. An analysis of available manpower and materials had shown that it was not possible to build the pipeline in less than two winters. This coincided with the time required to develop the oil field and processing facilities so that both would be completed at the same time.

Special permission from government agencies had been given to start "pre-construction" work before the end of the two year time delay and this allowed the 30 metre pipeline route to be cleared of trees and all preparations made for the main construction groups. By awarding the pre-construction contracts to Northern companies, particularly native groups, it was possible to increase the benefits to Northern people and the separating of the work forces allowed different rates of progress.

There is a great incentive to complete the pipeline on schedule when the overrun costs are considered. The loss of oil field production for one year and the cost of interest on the total investment for one year is enormous and suggested that incentives be used to encourage fast pipeline construction. Incentives were not needed on pump station construction because work can take place in either summer or winter.

The entire length of the pipeline was divided into six "construction spreads" each of which would work for one winter season. These are shown on Figs. 2 and 6 and to provide an incentive it was decided that the spreads #1 and 2 would work towards the south and spreads #3 and 4 would work towards the north. The crossing of the Mackenzie River would be a separate contract. Spreads 5 and 6 moved northwards but had access from both ends.

There would be three separate contractor groups each having two sections of work. It was known that contractor costs for the second year would be higher than the first year because of escalating labor and other costs which were occuring in Canada at that time. The contractors were encouraged to complete more than one section of work in the first winter by agreeing to pay the second year prices for the additional production. In the second year, two contractors would be working towards each other, one from the north and one from the south. It was planned that if one contractor did not meet the required production rate, some of his work would be taken away and awarded to the other contractor.

The results of these incentives were that the pipeline was completed within the timetable and at only a small increase in the incentive costs.

Contractors

In Canada large pipeline contracts are awarded on the basis of competitive bids. Most of the larger contractors operate under agreements with several trade unions and on this project it was important to ensure that there was no work stoppages due to disagreement between the unions and contractors. The Company proposed a "no-strike agreement" for the duration of the project and after agreeing to a common wage policy for all contractors, an agreement was signed which covered 19 different trades and lasted until the completion of the work. Any labor disputes which arose were settled without the need to strike and no time was lost.

For effective control of costs, the contract documents must clearly and accurately date the following:

1) Scope of Work;
2) Contractor Obligations and Responsibilities;
3) Owner Obligations and Responsibilities;

4) Contractor Price and Price Breakdown by Systems;

5) Method of Compensation;

6) Rates for Extra Work;

7) Contractor Equipment and Manpower Schedules;

8) Contractor Work Schedule;

9) General Conditions;

10) Special Conditions (Environmental, Socio-Economic, Archaeological);

11) Design Information;

12) Construction Specifications;

13) Procedure for Identifying Extra Work.

A lump sum price per linear metre was required and a fixed move-in and move-out cost was to be quoted. For special items of work such as concrete weights, additional depth of ditch etc. unit prices were quoted which could be applied to the actual quantities.

A construction schedule submitted with the bid provides the basis for subsequent comparison of actual and scheduled progress. Fig. 6 shows the resultant production. If the work falls behind schedule the pipeline company retains the right to direct the contractor to increase the work force or equipment and if this is still not successful can take over the work itself. This is rarely needed in Canada as contractors are motivated by the desire to complete the work and then be paid.

Construction Inspection

Pump stations, maintenance areas and other similar facilities built by contract were continuously inspected by the Construction Management Group for both quality and production rates.

Mainline construction required a team of about twenty five inspectors per spread to which is added radiographic personnel for weld inspection and a clerical group. The total for the most northerly spread would be about forty people all in radio contact to a central office and the chief inspector. A small survey group records the actual location of the pipeline and provides a ground profile on completion.

Financial Controls

The financing of major projects is generally supported by the use of borrowed funds. In this project it was decided by the Company and agreed to by the National Energy Board that 75% of the investment would be borrowed from the financial market and 25% would come from the Company's own sources. This is a common "debt" to "equity" ratio for such projects. Funds were made available to meet demands based on a financial forecast which in turn is based on the timing of major material and construction purchases.

Cost Management

Within the financial controls group, one of the most important areas is cost management. This item is important on any major project, but in remote areas there is a greater chance of error and other factors such as weather which can lead to major cost overruns.

On a project which has almost 3000 separate orders and contracts which vary from simple lump sum payments to complicated contracts worth several million dollars there must be an integrated control system to minimize errors and subsequent costs.

Fig. 9 shows in a diagramatic way, the process which was used. The essential elements are as follows:

- The comparison and analysis of actual costs to the control estimate.

- Corrective action to bring the actual costs into line with the control estimate.

- Measurement of the results of any corrective action.

It will be realized that the production of the <u>control</u> <u>estimate</u> is the basis from which all future comparisons are made. This estimate is most carefully prepared at the time a decision is made to proceed with the project and provides the best possible figures prevailing <u>at</u> <u>that</u> <u>time</u>. The quality of the estimate depends on the degree of knowledge (or ignorance) of the components and an allowance or <u>contingency</u> factor is provided. These factors vary generally from 1.00 to 1.35 at this stage of a project, and each section of the estimate was carefully scrutinized before the figure was agreed upon.

As work is completed, unused funds from these contingency items are removed so that they cannot be used for other items. Additional funds needed for cost overruns can only be obtained by approval of senior management who would require a satisfactory explanation why the control estimate is being exceeded.

Some cost increases are not due to human error such as landslides, flooding, early thawing etc. and provision is made in the control estimate for such an event. On this project the figure was roughly $50 million but in practice was not needed.

It would be almost impossible to manage such a large amount of data without the use of computers and several programs are now available on the market to assist in project cost management. They allow continuous checking of incoming costs and provide a forecast to completion. The forecasting will result in necessary corrective action taking place and assist management to check the results of this action.

Appendices 2A and 2B show copies of some of the computer printouts. 2A shows the final major cost items and it will be seen that the project was completed at $355 million with a control estimate of $450 million.

The cost overruns and underruns can be seen and it will be noted that the special contingency item which is named "project reserve" was not used. 7B shows how this method was applied to section #1 of the main pipeline and the individual components can be seen. A similar process was used for the entire project which requires large printouts, but provided important management support on a monthly basis.

The accounting and printing format was also acceptable to the National Energy Board and copies of these detailed reports were sent for their information.

The project management included an audit process which checked the accuracy and reporting of all costs, this was supplemented by a separate audit group paid for by the Company but independent from it. The National Energy Board as the principle government agency conducted its own audit of costs so that the final capital costs were agreed by all parties and was used to calculate the resulting tariff.

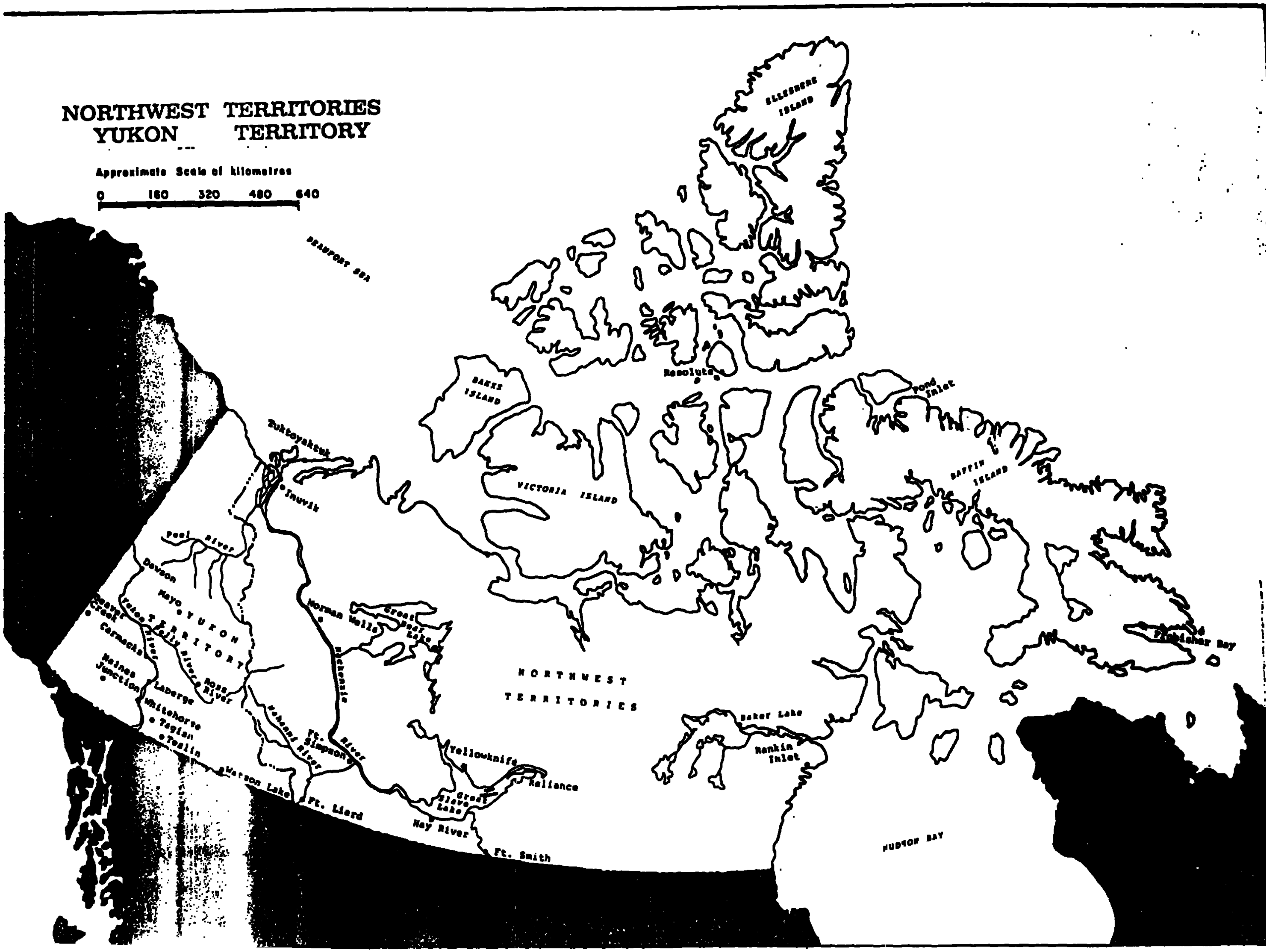
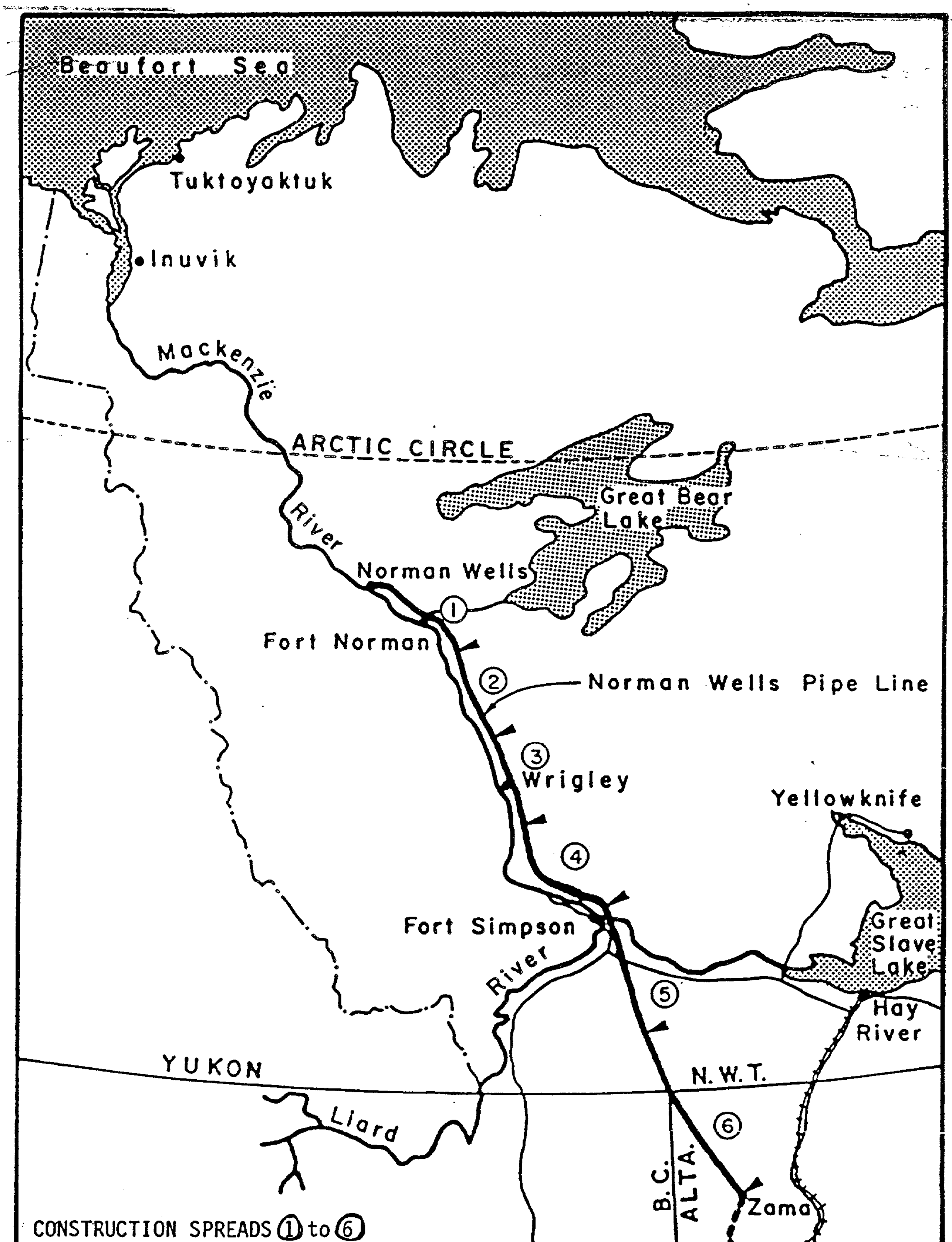

NORTHWEST TERRITORIES
YUKON TERRITORY
Approximate Scale of kilometres
0 160 320 480 640
BEAUFORT SEA
ELLESMERE ISLAND
BANKS ISLAND
Resolute
Pond Inlet
VICTORIA ISLAND
BAFFIN ISLAND
Tuktoyaktuk
Inuvik
Peel River
Dawson
Mayo
YUKON TERRITORY
Beaver Creek
Yukon River
Carmacks
Pelly River
Ross River
Haines Junction
Laberge
Whitehorse
Tagish
Teslin
Watson Lake
Ft. Liard
Norman Wells
Great Bear Lake
Mackenzie
Ft. Simpson
River
Yellowknife
Reliance
Great Slave Lake
Hay River
Ft. Smith
NORTHWEST TERRITORIES
Baker Lake
Rankin Inlet
Frobisher Bay
HUDSON BAY

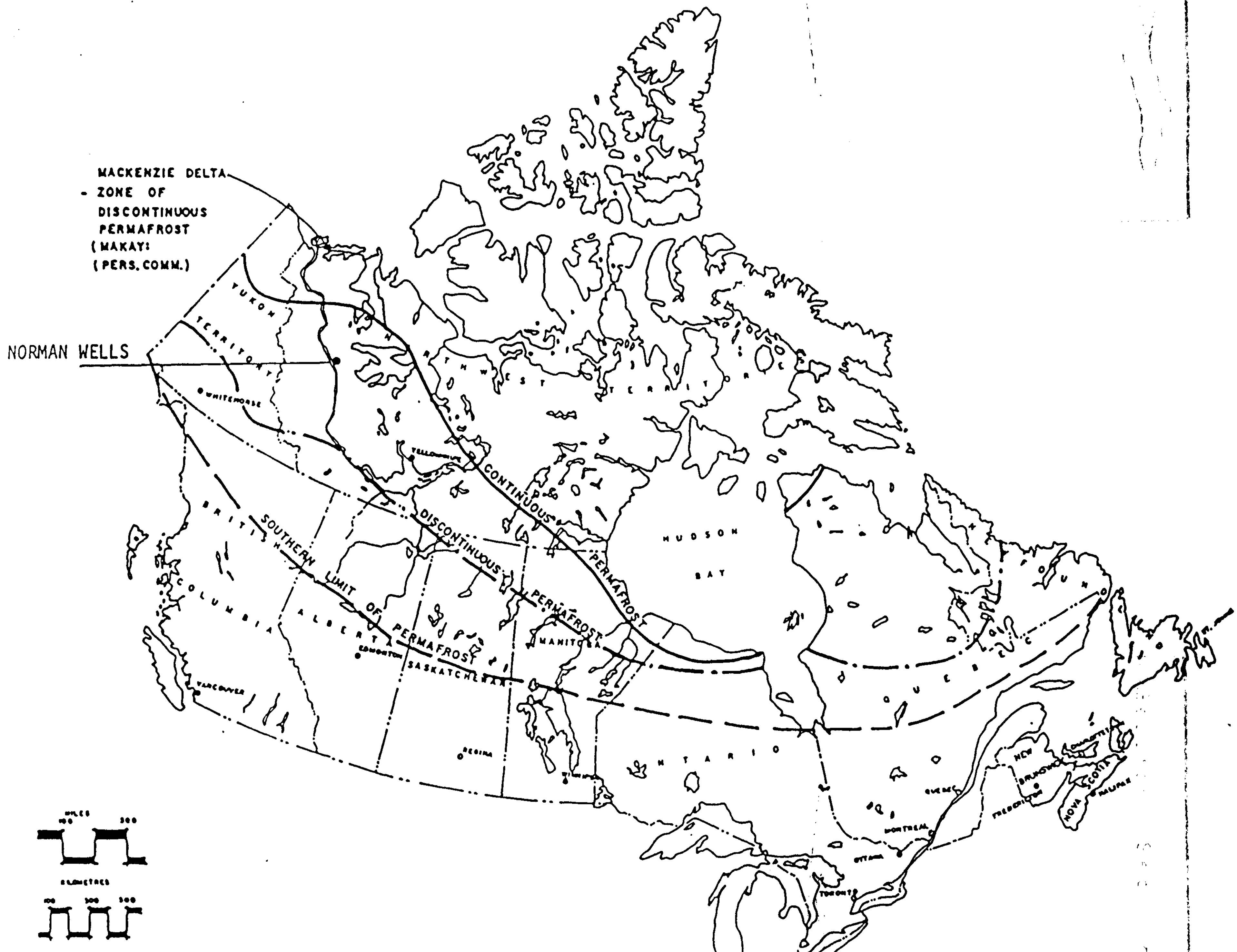
FIGURE 1

FIGURE 2

FIGURE 2



Permafrost in the Northwest Territories



REDRAWN FROM SOURCE: NAYSMITH; NORTH OF 60; LAND USE AND PUBLIC POLICY IN NORTHERN CANADA, Pg. 207

FIGURE 3

INTERPROVINCIAL PIPE LINE LIMITED

Company Organization Chart for Norman Wells Pipeline

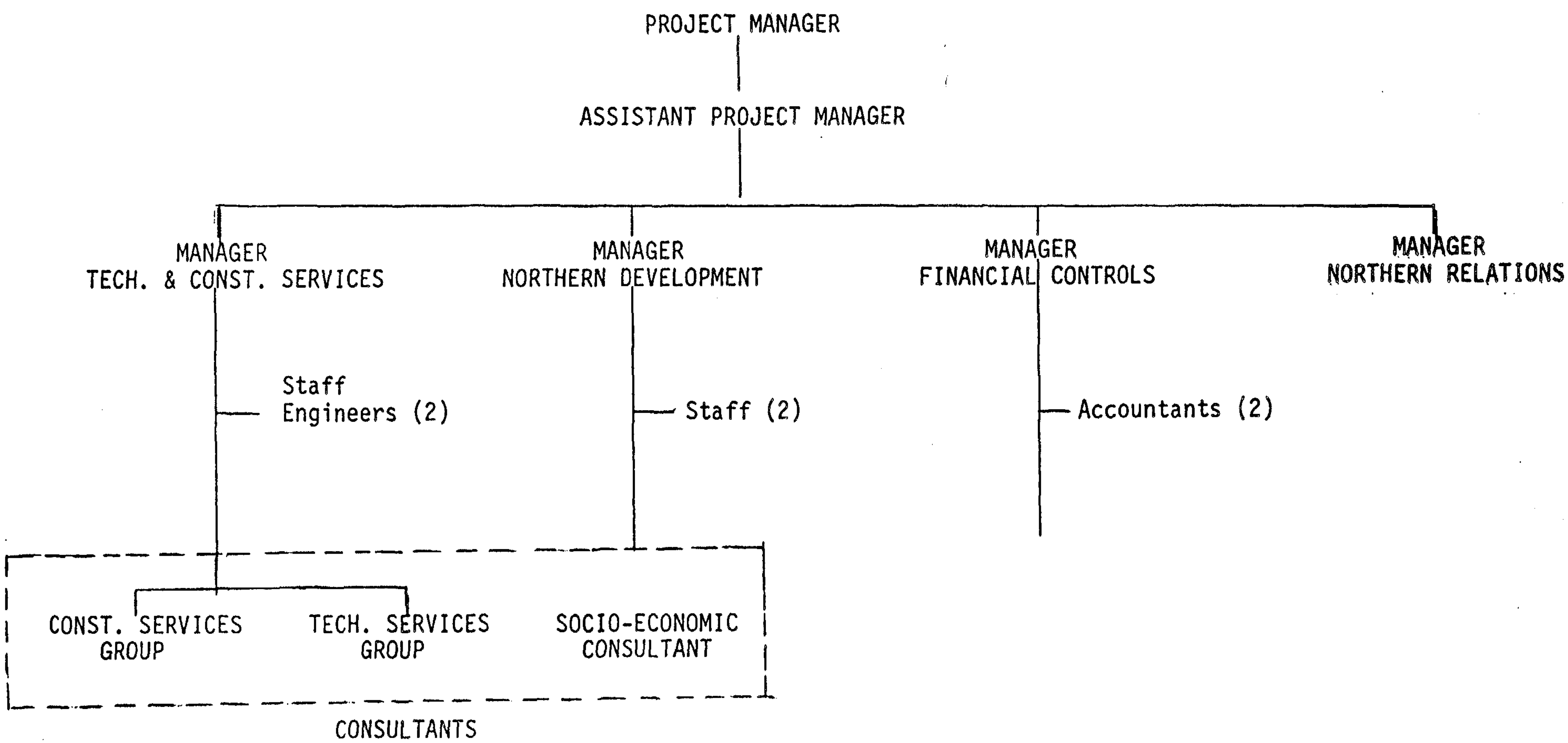
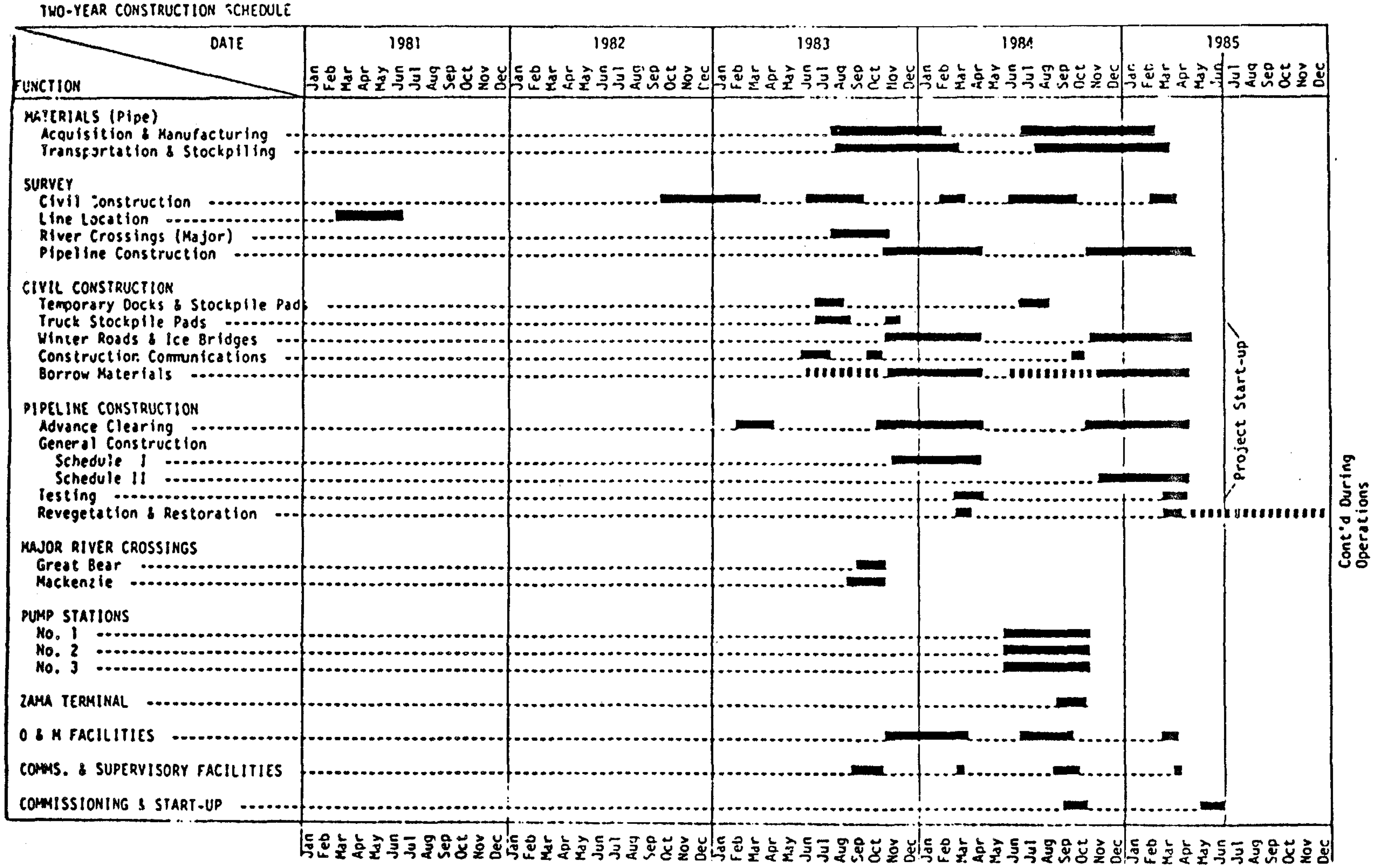


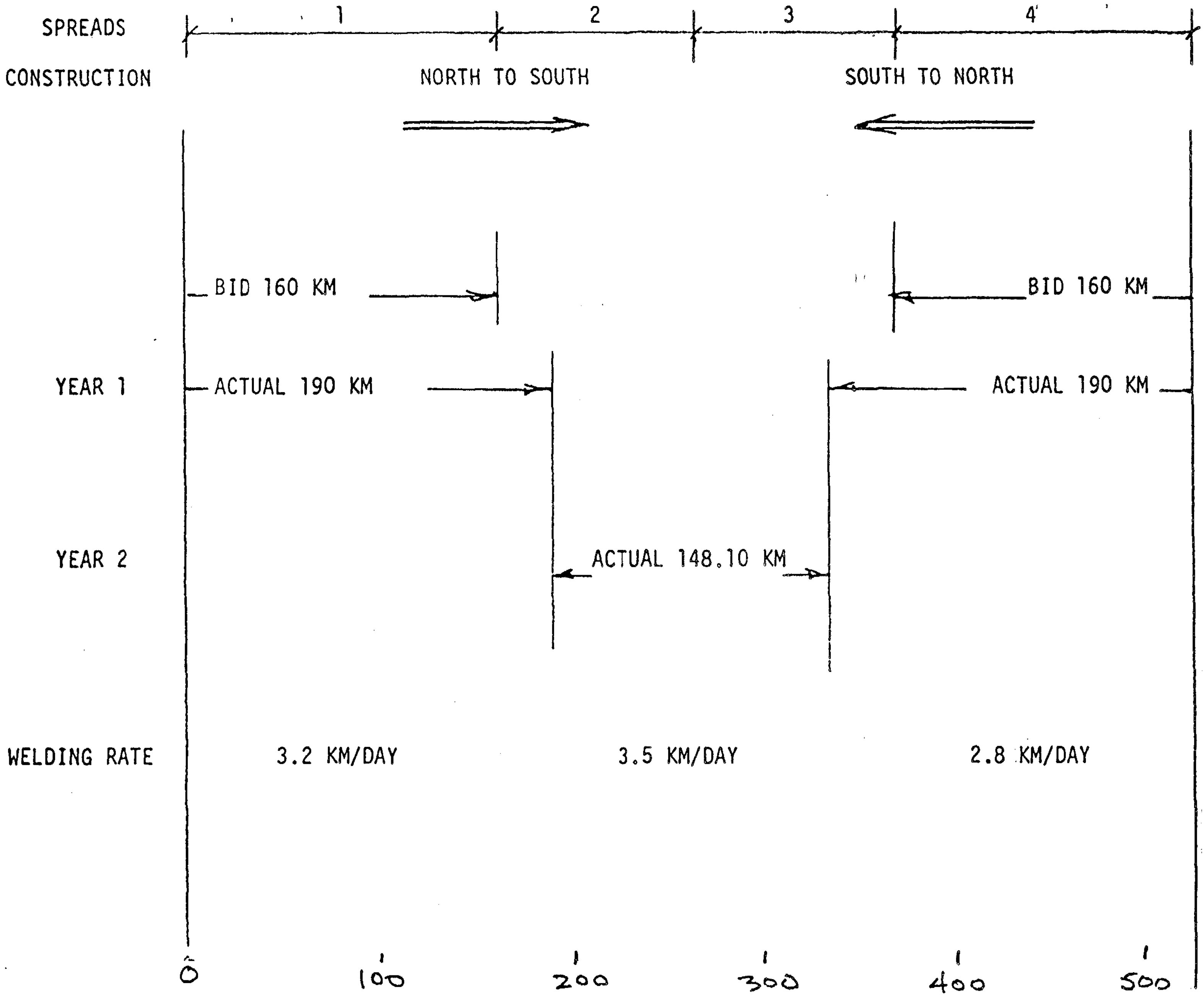
FIGURE 4

FIGURE 5

TWO-YEAR CONSTRUCTION SCHEDULE



February, 1982



NORMAN WELLS SPREAD SUMMARY FOR 1 TO 4

FIGURE 6

NORMAN WELLS PIPE LINE
COST MANAGEMENT

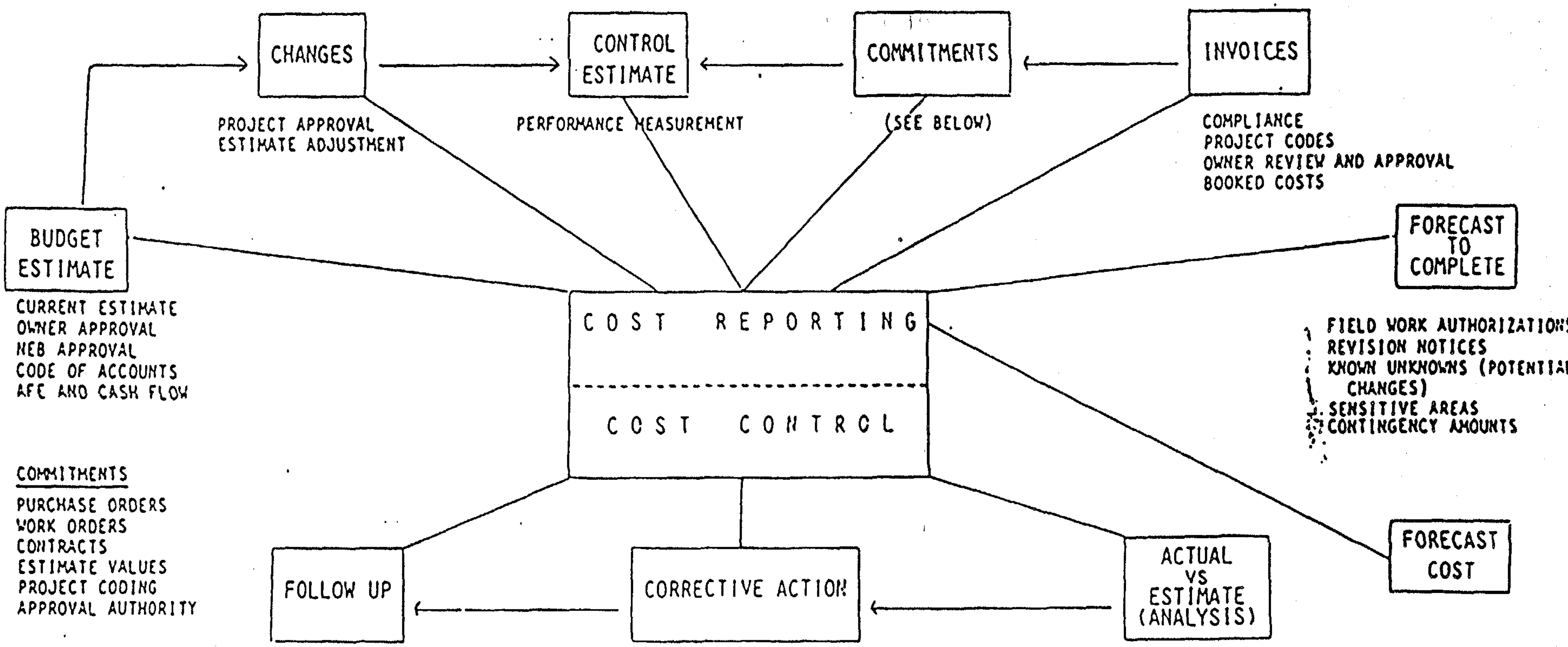


FIGURE 7

LIST OF SOCIOECONOMIC AND ENVIRONMENTAL STUDIES

NORMAN WELLS PIPE LINE PROJECT

SOCIOECONOMIC MATERIAL

1. Prepare and develop the key elements of each of the socioeconomic plans and programs which the applicant undertook to carry out:

   a. Information and consultation action plan
   b. Northern business opportunities action plan
   c. Orientation action plan
   d. Construction manpower delivery action plan
   e. Operation and maintenance training and employment action plan
   f. Medical services action plan
   g. Employee housing action plan
   h. Security action plan
   i. Monitoring action plans

2. Northern Alberta

   a. Update the socioeconomic impact assessment

3. Six months following end of 1st year of operation

   a. Submit report on actual socioeconomic impact of the project, including the Norman Wells field development

ENVIRONMENTAL MATERIAL

1. Provide reassessment of plans for minimizing terrain damage (literature review, fieldwork, etc.)

2. Thaw settlement, frost heave, etc..

   a. Evaluation of extent and incidence of frozen/unfrozen reaches (for more accurate design)
   b. - Subsurface investigation data base for quantifying high, medium and low ice contents
      - Settlement magnitude prediction
   c. Frost heave analysis (as proposed OK). Also identify rivers and streams where frost heave may be a problem and provide proper design.

3. Sensitive slopes and river crossings

   a. Results and data from field investigations for evaluation of slopes which may become unstable and for water crossings and approaches
   b. Results of river crossing studies to be submitted
   c. Drainage and erosion - final design requires the program for preserving stability of slopes
   d. Shallow seismic program for Great Bear and Mackenzie Rivers

4. Borrow locations and hauling routes, roads, etc.

    a. Assessment of development, operation, abandonment and rehabilitation of pits and material movements
    b. Identify areas where high ice content or poor grade material will be disposed of
    c. Environmental assessment including impact on terrain, wildlife and aquatic resources (fieldwork)
    d. Detailed rehabilitation plans

5. Aquatic Resources

    a. Mitigative measures for fish resources in the vicinity of water crossings
    b. File site specific studies applicant undertook to provide and a description of the proposed mitigative measures to be adopted
        i. Late Winter Survey
        ii. Facility sites
        iii. Major River Crossings

6. Birds of Prey

    a. Results of study to identify species occupying nests within 3.2 km of field construction activities and mitigative measures including endangered status of peregrine falcon (note confidentiality of data)

7. Wildlife

    a. Additional studies to verify mitigative measures and site specific data to reduce impacts
        i. Waterfowl study
        ii. Facility site study
        iii. Proposed ungulate monitoring
    b. Revised construction timetable to include specific mitigative measures, if required for wildlife, fish, raptors

8. Awareness programs, procedures and inspection staff education

    a. Program for environmental education of inspection and construction staff
        i. Clearing and preconstruction
        ii. Construction
    b. Program for construction and environmental inspection including organization and reporting, etc.
    c. Provide an environmental procedures manual (environmental protection plan)
        i. Detailed outline of EPP
        ii. Environmental protection
        iii. EPP Clearing Winter 82/83
        iv. EPP Clearing & Site Development 82/83

9. **Archaeology**

   a. **Mitigative measures as recommended by Consultant**

10. Contingency Plans For Emergencies

    a. Regarding the handling and storage of fuels, lubes and toxic chemicals, forest fires and changes in construction scheduling.

INTERPROVINCIAL PIPE LINE (NW) LTD.
COST REPORT BY PLANT ACCOUNT

AFE NUMBER: N3110 REPORT ENDING: 11/30/1986

PLANT ACCOUNT		1. CONTROL ESTIMATE	2. BUDGET CHANGES/ TRANSFERS	3. REVISED CONTROL ESTIMATE 1+2	4. COMMITMENT TO DATE	5. INVOICES PASSED FOR PAYMENT	6. FORECAST TO COMPLETE ABOVE COL. 4	7. FORECAST PROJECT COST (4+6)	8. OVER UNDER (-) BUDGET (7-3)
151	LAND	137,120	32,182	169,302	115,493	115,614	0	115,493	-53,809
152	LAND RIGHTS	479,770	0	479,770	379,052	379,052	0	379,052	-100,718
153	PIPELINES	249,579,400	-34,102,786 *	215,476,614	211,597,389	211,453,019	5,047,743	216,645,132	1,168,518
156	BUILDINGS	14,648,195	-5,846,289 *	8,801,906	8,357,711	8,289,705	310,279	8,667,990	-133,916
158	PUMPING EQUIPMENT	4,673,472	-1,579,070	3,094,402	2,978,954	2,978,950	172,639	3,151,593	57,191
159	STATION OIL LINES	1,005,556	-138,681	866,875	1,124,628	1,124,628	0	1,124,628	257,753
160	OTHER STATION EQUIPMENT	3,688,299	40,120 *	3,728,419	4,020,229	3,965,059	59,025	4,079,254	350,835
161	OIL STORAGE TANKS	2,432,500	-2,432,500 *	0	0	0	0	0	0
163	COMMUNICATION SYSTEMS	148,925	181,239 *	330,164	295,165	266,877	0	295,165	-34,999
184	OFFICE FURNITURE AND EQUIPMENT	273,232	20,080	293,312	174,543	174,662	0	174,543	-118,769
185	VEHICLES AND OTHER WORK EQUIP.	6,543,548	-1,803,911	4,739,637	5,831,725	5,831,050	115,489	5,947,214	1,207,577
186	COMPUTERS & SOFTWARE	1,150,000	270,000	1,420,000	1,041,998	1,042,295	3,558	1,045,556	-374,444
189	INTEREST DURING CONSTRUCTION	62,879,946	-11,236,946 *	51,643,000	48,696,202	48,696,202	0	48,696,202	-2,946,798
190	OVERHEAD DURING CONSTRUCTION	53,360,037	10,596,562 *	63,956,599	63,046,783	62,787,274	1,631,395	64,678,178	721,579
		401,000,000	-46,000,000	355,000,000	347,659,872	347,104,387	7,340,123	355,000,000	0
199	PROJECT RESERVE	49,000,000	-49,000,000 *	0	0	0	0	0	0
		450,000,000	-95,000,000	355,000,000	347,659,872	347,104,387	7,340,128	355,000,000	0

APPENDIX 2(a)

test sites, a design differential thaw settlement of up to 0.8 m was established for mineral soils and 1.2 m for thick organic soil deposits.

Frost heave. IPL studies revealed that in general, the frost bulb formed around a shallow buried pipe wall forms part of the larger layer of seasonal frost and that the overall stiffness would prevent excessive curvature. At some stream crossing and overland sections of deeper buried pipe, the frost bulb around the pipe may not form part of the seasonal frost.

Sag bends were identified as being particularly sensitive to this effect with potential for increasing the compressive strain in the pipe. Frost heave potential at sensitive locations was evaluated and used as input for stress analysis of the pipeline.

The analysis revealed that the critical strain was exceeded on tangent pipe adjacent to sag bends at the base of frozen slopes, greater than 10°. Consequently, the sag bends at such sites were insulated to prevent the formation of a frost bulb.

Slope evaluation. The Norman Wells pipeline crosses a large number of slopes, many of which are susceptible to downslope movement as a result of thermal degradation.

Office, field, and laboratory programs were carried out to define the required design parameters. Four modes of slope failure were considered in the analyses:

1. Deep seated failure
2. Infinite slope failure
3. Infinite slope failure on a localized portion of the right-of-way
4. Backfill failure around pipe

A list of 150 significant slopes was prepared; these were slopes requiring site specific stability analyses and design. Most of these are north of the Willowlake River (km 0 to km 380).

Extensive analysis of slope stability resulted in a three-phase approach to slope evaluation:

1. Design phase: Determine which slopes are stable and establish practical mitigation for instability.
2. Construction phase: Follow rigid clearing and construction specifications to minimize sensitive slope disturbances; field geotechnical engineer evaluates and refines design to reflect actual conditions.
3. Operational monitoring phase: Monitor slopes during operations particularly in respect to geothermal conditions and groundwater regime.

From the geotechnical studies, three mitigation concepts were developed:

- Prevent thaw (for highly ice-rich slopes). In such a design, thaw is restricted to the natural active layer.
- Retard thaw. In certain slopes, thaw advancement is permitted at a controlled rate.
- Cut back slopes. For unavoidable slopes that are sufficiently steep to be inherently unstable, cutting back is required to ensure long-term stability.

The geotechnical studies revealed a significant relationship between the depth of thaw and width of clearing. Although on most of the route a 25-m right-of-way was cleared, on sensitive slopes a clearing of 13 m was specified to retard thawing effects.

IPL concluded that wood chips were a suitable insulation for thaw prevention or retardation. Depths of 0.5 to 1.5 m have been specified for certain slopes. Slope design guidelines are summarized in Table 2.

Pipeline design. Various aspects of the design of the pipeline have been described in some detail.[1] The Oil Pipeline Regulations of the NEB specify requirements for the design and include requirement for compliance with Canadian Standards Association CSA Z183-M1982.

The pipeline has been designed to withstand two types of loadings, primary and secondary.

The former includes circumferential stress due to internal pressure. This stress is limited to 72% of the specified minimum yield strength (SMYS) of the pipe by CSA Z183. The code further restricts the maximum shear stress resulting from internal pressure and thermal effects to 45% of SMYS.

Secondary loadings which are displacement restrictive, such as those imposed by thaw settlement and frost heave, are limited by maximum allowable strain. Buckling analysis and maximum energy distortion criteria defined the maximum compressive strain at 0.5% in consideration of both primary and secondary loadings. This value allows a factor of safety of 1.3, discounting seismic effects.

The maximum allowable operating pressure (MOP) for the pipeline is 9,930 kilopascals (kP's 1,440 psi).

The temperature differential to be considered during design is the maximum difference between the temperature of the flowing oil and the thermally stress-free reference temperature of the pipeline when laid in the ditch and backfilled. The temperature differential in the stress analysis was 36° C., corresponding to a reference temperature of −30° C. and maximum operating temperature of +6° C.

As a result of the studies, differential thaw settlement values were set for various segments of the pipeline: 0.8 m for the first 78 km, 0.75 for 78 to 440 km, and 0.70 for permafrost areas over the rest of the route.

For areas of deep peat, design thaw settlements of 1.2 m were predicted. A transition length of 1.5 m was selected as a conservative distance over which a transition could occur.

As a result of thaw settlment loading analysis, approval was obtained from the NEB to vary the general requirement for cover from 1.0 m to 0.76 m resulting in significant reductions in pipe loading at transitions and wall thickness of the pipe.

It was determined that the governing factors in pipe design would be the structural response of the pipe to loadings caused by differential settlement and frost heave. Stress analysis was carried out using a three-dimensional finite element computer program which considered both elastic and plastic deformation of the pipe.

The wall thicknesses were selected (Table 3) from the stress analyses.

Pump station design. The optimal initial configuration of pumping capacity calls for three pump stations along the pipeline. This number allows for future expansion of capacity if needed by the addition of three intermediate stations.

Fuel cost considerations call for operation of the Norman Wells pump station at or near MOP in order to maximize power use. The next priority for pumping is at the third pump station south of Fort Simpson with the second station near Wrigley being used only to maintain throughput.

Pump stations are designed with two 100% units, one for backup. The Norman Wells station is powered by dual fuel engines (natural gas/propane); the other two stations are fueled with diesel either trucked in winter or barged in summer.

Pump drivers at each station are as follows: Norman wells: 2 @ 721 kw; Wrigley: 2 @ 245 kw; and, Mackenzie Highway: 2 @ 561 kw.

Sectionalizing valves. The pipeline regulations require the placement of mainline sectionalizing valves at a spacing not exceeding 30 km. With a computer program with a ranking system for sensitive areas, valve locations were determined to meet regulatory requirements while ensuring that spills resulting from line ruptures were reduced in sensitive areas.

The use of remotely operated valves and a leak detection system to protect sensitive areas has been incorporated into the pipeline design. All remotely controlled valves are operated by radio controlled, thermal-electric/hydraulic powered valve operators.

Communications. Communications planning was divided into construction and operations. The main requirements during construction were for worker pay phones in camps and for mobile voice communications for contractors and supervisory staff.

For operations, communications requirements are to operate the supervisory control and data acquisition system (SCADA) and to provide mobile voice communications for maintenance and operating staff.

Most pipeline data points are connected by UHF/VHF links to a receiver on an existing telephone company microwave tower. All remote valves and pump stations are connected through an RTU by modem radio-to-microwave link to a computer in the Norman Wells operation center.

Construction

Right-of-way clearing was started during the winter of 1983. Northern contractors cleared about 500 km of right-of-way. During the winter of 1984, the balance of the right of way was cleared.

Also that winter, grading of the right-of-way started during the first week of December and in the winter of 1985 the work started during the last week of November.

Stringing of pipe was done with conventional stringing trucks hauling from pre-established stock piles. Pipe was procured precoated with the coating contractor responsible for delivering holiday-free pipe to the pipeline contractor at the stockpiles.

All bends were made in the field with a bending machine. Extremely cold temperatures caused minimal problems with the pipe coating.

Welding was done with two crews on each spread. In spite of extreme cold, good progress was achieved with rates of 175 welds per crew-day commonly achieved. Lost welding time due to weather was minimal over the two winters of mainline construction (Fig. 3).

Ditching posed a major hurdle for the contractor working on the northern spreads. Use of two "Arctic" ditchers per spread and up to nine backhoes and double shifting allowed progress to be maintained during the first winter of mainline construction.

Frozen soils with a high content of small to medium sized boulders proved difficult. Ground had to be ripped prior to ditching.

In the construction spreads south of the MacKenzie River, the ditching effort was more conventional, being handled by five Barber Green 77A ditchers and two backhoes. Working one shift, the ditching operation was able to stay ahead for lowering in.

Backfilling provided some unique challenges due to a lack of good select material for padding in bouldery areas. To maintain progress, when suitable soil was unavailable, the contractor used a "lizard" to protect the pipe; culled out very large boulders from the backfill prior to placement; and in some areas used field-applied polyurethane padding.

The authors...

Pick

Smith

A. R. Pick is manager for technical and construction services, Interprovincial Pipe Line (NW) Ltd., Edmonton. He joined the Norman Wells project team in 1982. Before that time, he was vice-president of MacLaren Plansearch Service Ltd., Edmonton. A Registered Professional Engineer, Pick holds a BSE and an MSc from the University of North Dakota.

J. D. Smith is a senior engineer with 10 years' service for IPL. On the Norman Wells project, he was senior staff engineer. He holds a BEng in civil engineering from the University of Alberta.

Testing of the Norman Wells pipeline was done with compressed air. Following a 4-hr strength test at 125% of MOP, a 36-hr leak test was performed. Following air testing, a caliper pig was run.

To eliminate ice and water in the line, a methanol wash was run. Test sections varied from 20 to 30 km.

After line fill, prior to placing the line in service, a leak test was conducted with crude oil. The test, in three sections, sectionalizing at the pump station, showed that the leak test conducted using air was valid.

Crossings of the Mackenzie River and the Great Bear River were constructed during the summer of 1984.

The Great Bear River crossing was excavated by backhoe. Bed material consisted of poorly consolidated fractured sandstone and gravel.

The Mackenzie River crossing was constructed in bedrock over half the width of the river. The mudstone was drilled through the ice and blasted in February of 1984. During August the ditch was excavated and the pipe laid.

For both crossings, the concrete coated pipe was assembled on shore and pulled into the ditch. The crossings were hydrostatically tested after backfilling.

The use of wood chips as insulation for permafrost slopes is a unique application. The selected coniferous trees were decked and chipped at the wood lot. The chips were blown into vans and hauled to the slope and spread by a small tractor.

As the final step, sand bag erosion control berms were built and disturbed areas of the right-of-way fertilized and seeded before spring thaw.

The construction procedures used on the Norman Wells pipeline project were highly conventional with the laying equipment being larger than needed because of availability.

Environmental concerns. During the regulatory approvals stage, IPL performed a significant number of studies and submitted the reports for regulator and intervenor review.

IPL developed an ongoing program for the environmental education of all project staff including contractors' personnel. The indoctrination of all personnel in respect to the environmental and socio-economic issues of the project was mandatory to ensure that all project personnel understood the environmental protection commitments made by IPL.

An environmental inspection program was developed by IPL whereby each operation was scrutinized to verify that the environmental protection commitments were fulfilled.

The principal issues identified by the studies included terrain disturbance in permafrost and wildlife conflicts. IPL implemented a progressive wildlife management policy allowing for compensation of hunters or trappers adversely affected by the pipeline.

Archaeological surveys were conducted along the right-of-way and significant sites were protected.

Monitoring. IPL is conducting an extensive monitoring program in cooperation with INAC and the GNWT to verify that the predictions made during the regulatory and design process are valid.

The program focuses on observation of terrain conditions, geothermal conditions, frost heave, thaw settlement, wildlife, and habitat responses for periods sufficient to verify that equilibrium conditions have been established or that no significant disturbance has occurred.

The monitoring program is based on extensive instrumentation and observation on a regular basis for a minimum period of 3-5 years after construction. Aerial photography of the complete alignment will be done for 5 consecutive years.

This project is viewed by many as a pilot project, a precursor to significant resource development in the Mackenzie Valley and Beaufort Sea.

References

1. Nixon, J.F., Stuchly, J., Pick, A.R., 1984, Design of Norman Wells Pipeline For Frost Heave and Thaw Settlement. 3rd International System on Offshore Mechanics and Arctic Engineering, ASME Trans. of Journal of Energy Resources

INTERPROVINCIAL PIPE LINE (NW) LTD.
DETAILED COST REPORT BY LOCATION

AFE NUMBER: N3110 REPORT ENDING: 11/30/1986

AT LOCATION: 11 MAIN LINE SPREAD NO. 1

PLANT CODE	SYSTEM CODE	SYSTEM DESCRIPTION	SUB SYSTEM CODE	SUB SYSTEM CODE DESCRIPTION	1. CONTROL ESTIMATE	2. BUDGET CHANGES/ TRANSFERS	3. REVISED CONTROL ESTIMATE 1+2	4. COMMITMENT TO DATE	5. INVOICES PASSED FOR PAYMENT	6. FORECAST TO COMPLETE ABOVE COL. 4	7. FORECAST PROJECT COST (4+6)	8. OVER UNDER (-) BUDGET (7-3)
52	02	LAND RIGHTS			79,941	0	79,941	59,988	59,988		59,988	-19,953
53	07	PIPE	AA	IPSCO	5,994,643	-130,389	5,864,254	5,869,587	5,869,589	0	5,869,587	5,333
			AB	PIPE MILL INSPECTION	0	39,689	39,689	39,689	39,689	0	39,689	0
	07				5,994,643	-90,700	5,903,943	5,909,276	5,909,278	0	5,909,276	5,333
53					5,994,643	-90,700	5,903,943	5,909,276	5,909,278	0	5,909,276	5,333
53A	08	FITTINGS			209,428	-24,333	185,095	180,714	180,714		180,714	-4,381
53B	09	CONSTRUCTION COSTS	AA	IPL - OTHER COSTS	113,705	51,178	164,883	185,636	185,636	0	185,636	20,753
			AB	IPL 'COPTER ACT TO 3/31/83	48,123	-1,360	46,763	46,763	46,763	0	46,763	0
			AC	TRAPPER SETTLEMENTS	49,999	0	49,999	0	0	0	0	-49,999
			AE	NORTHWESTEL MAINT. CHARGES	17,500	-17,500	0	0	0	0	0	0
			BA	PRE-CLEARING (UNALLOC.)	0	0	0	0	0	0	0	0
			BB	MACK. MTN.	357,375	0	357,375	357,375	357,375	0	357,375	0
			BC	FT. NORMAN CONST.	875,132	11,250	886,382	886,382	886,382	0	886,382	0
			BD	PRE-CLEARING (MISC)	92,928	-76,928	16,000	16,000	16,000	0	16,000	0
			CA	INFRARED SURVEY	1,368	-484	884	884	884	0	884	0
			DA	SITE DVLP (UNALLOC)	82,205	-82,205	0	0	0	0	0	0
			DB	KENASTON (KP 78)	804,834	0	804,834	804,834	804,834	0	804,834	0
			DC	SITE DVLP (MISC.)	96,198	2,107	98,305	98,305	98,305	0	98,305	0
			EA	M/L CONST. (PE BEN)	32,718,292	-3,737,622	28,980,670	28,987,544	28,987,544	0	28,987,544	6,874
			EB	BLOCKS & SKIDS	138,591	29,548	168,139	168,139	168,139	0	168,139	0
			EC	KINGS WELDING	267,506	8,640	276,146	276,146	276,146	0	276,146	0
			ED	NORTHERN TRANSPORT CO	133,513	1,243	134,756	134,756	134,756	0	134,756	0
			EE	CONC. WEIGHTS	496,200	-226,242	269,958	271,720	271,720	0	271,720	1,762
			EF	SAND BAGS	738,973	55,644	794,617	821,224	821,224	0	821,224	26,607
			EG	MISC. ITEMS	221,492	287,300	508,792	392,916	392,916	0	392,916	-115,876
			EH	INITIAL FUEL SUPPLY	153,359	12,054	165,413	162,470	162,470	0	162,470	-2,943
			EI	RESTORATION & RESEEDING	707,979	-140,113	567,866	1,898,224	1,898,224	0	1,898,224	1,330,358
			FA	NON-DEST. TEST	760,363	-330,720	429,643	418,628	418,628	0	418,628	-11,015
			GA	CSM SUPR & INSP (LAB)	1,268,850	-308,959 *	959,891	1,108,256	1,108,256	0	1,108,256	148,365
			GB	CSM SUPR & INSP (EXP)	288,945	-120,851 *	168,094	186,209	186,209	0	186,209	18,115
			GC	CSM FIELD VEHICLE EXPENSES	175,915	52,610 *	228,525	232,172	232,172	0	232,172	3,647
			GD	CSM HELICOPTERS	218,330	-79,738 *	138,592	220,763	220,763	0	220,763	82,171
			HA	CSM (LABOUR)	0	0	0	19,409	4,022	0	19,409	19,409
			HB	CSM (EXPENSE)	0	0	0	98	4,639	0	98	98
			HD	CSM (HELICOPTER)	0	0	0	0	0	0	0	0
			IA	PIPE MILL INSPECTION	38,816	-38,816	0	0	0	0	0	0
			IB	PIPE COATING & TRANSPORT	2,758,394	0	2,758,394	2,693,926	2,693,924	0	2,693,926	-64,468
			JA	REMOTE MLV STATIONS	13,600	26,585 *	40,185	45,845	45,845	0	45,845	5,660

APPENDIX 2(b)

INTERPROVINCIAL PIPE LINE (NW) LTD.
DETAILED COST REPORT BY LOCATION

AFE NUMBER: N2110 REPORT ENDING: 11/30/1986

AT LOCATION: 11 MAIN LINE SPREAD NO. 1

PLANT CODE	SYSTEM CODE	SYSTEM DESCRIPTION	SUB SYSTEM CODE	SUB SYSTEM CODE DESCRIPTION	1. CONTROL ESTIMATE	2. BUDGET CHANGES/ TRANSFERS	3. REVISED CONTROL ESTIMATE 1+2	4. COMMITMENT TO DATE	5. INVOICES PASSED FOR PAYMENT	6. FORECAST TO COMPLETE ABOVE COL. 4	7. FORECAST PROJECT COST (4+6)	8. OVER UNDER (-) BUDGET (7-3)
53B	09	CONSTRUCTION COSTS	SP	SPARE PARTS	0	36,853	36,853	24,828	24,828	0	24,828	-12,025
			XW	RESTORATION 85/86	0	0	0	336,565	357,420	0	336,565	336,565
			XY	WINTER 86/87 RESTORATION	0	0	0	0	0	768,765	768,765	768,765
			XZ	1987/88 ROW RESTORATION	0	0	0	0	0	360,000	360,000	360,000
	09				43,638,485	-4,586,526	39,051,959	40,796,017	40,306,024	1,128,765	41,924,782	2,872,823
53B					43,638,485	-4,586,526	39,051,959	40,796,017	40,806,024	1,128,765	41,924,782	2,872,823
56B	16	OTHER BLDGS(WELL;GAS;GARAGE)		OTHER BLDGS.	4,500	81,268 *	85,768	103,155	103,155	0	103,155	17,387
56G	23	FENCES			1,500	7,500 *	9,000	22,524	22,524	0	22,524	13,524
60C	39	REMOTE CONTROL		REMOTE CONTROL	47,150	0	47,150	80,695	80,695	0	80,695	33,545
			AB	REMOTE MLV STATION	0	73,232	73,232	73,232	73,232		73,232	0
	39				47,150	73,232	120,382	153,927	153,927	0	153,927	33,545
60C					47,150	73,232	120,382	153,927	153,927	0	153,927	33,545
63	48	RADIO COMMUNICATION SYSTEM	AA	IPL	0	0	0	0	0	0	0	0
85E	58	WATER POLLUTION CONTROL EQUIP.			0	0	0	8,571	8,571		8,571	8,571
					49,975,647	-4,539,559	45,436,088	47,234,172	47,244,181	1,128,765	48,362,937	2,926,849

AMERICAN SOCIETY FOR MECHANICAL ENGINEERS

PAPER No. 83-OMA-303 Presented at 3rd Intl. Symposium on OFFSHORE MECHANICS AND ARCTIC ENGINEERING, NEW ORLEANS FEB 12-16, 1984. ASME Trans. of Journal of Energy Resources Technolgy.

DESIGN OF NORMAN WELLS PIPELINE FOR FROST HEAVE AND THAW SETTLEMENT

J.F. NIXON
Hardy Associates (1978) Ltd.
Calgary, Canada

J. STUCHLY
Canuck Engineering Ltd.
Calgary, Canada

A.R. PICK
Interprovincial Pipe Line (NW) Ltd.
Calgary, Canada

ABSTRACT

Interprovincial Pipe Line (NW) Ltd. is constructing a 323 mm (12.7 inch) diameter buried oil pipeline from Norman Wells, Northwest Territories to Zama Lake, Alberta. The 868 km long pipeline crosses areas of discontinuous and intermittent permafrost resulting in difficult design problems particular to Arctic engineering.

Novel concepts have been developed and implemented for the design of the first fully buried oil pipeline in permafrost terrain. The basic design concepts include selection of the pipe diameter to limit the energy input to the environment, and to provide for an increased structural strength of the pipe to assure its integrity under conditions of loadings and displacement caused by thaw settlement and frost heave.

Loadings acting on the pipe have been identified and classified by their origin (pressure, temperature differential, thaw settlement, frost heave) and their type (primary; non-relieved by displacement and secondary; relieved by displacement). Both analyses and field observations were made to enhance the understanding of the loadings acting on the pipe as a result of thaw settlement or frost heave. Relevant models for analytical treatment of these phenomena were developed.

Design criteria for the pipeline have been established. Stress criteria, where applicable, have been used as defined by existing regulations. Strain criteria for displacement controlled loads have been established analytically. Thermal analysis and borehole data have been used to define values of thaw settlement and frost heave. Acceptable levels of local pipe deformation caused by a concentrated load (e.g. pipe pressing against a boulder) have been established.

Analytical approaches supported by field data and laboratory experiments have been used to define load displacement relationships for soil interacting with a buried pipe. Both gravity and shear loads were evaluated and defined for different thaw settlement and frost heave values. Maximum forces exerted on a buried pipe by a boulder have been evaluated and defined.

A three dimensional finite element inelastic computer model has been used to carry out the calculations for defining the wall thickness of the pipe required to assure conformance to the design criteria for the most critical loading combinations. Cases studied included thaw settlement, frost heave and bend analyses with the inclusion of seismic induced loadings. Significant results of the analyses are discussed in the paper.

The analyses completed confirmed the validity of the design concepts selected for the project. The resulting design proved to be economically viable. A monitoring program has been suggested which will allow for identification of thaw settlement, as the magnitude of the settlement approaches the design values.

INTRODUCTION

During the last fifteen years, several pipeline projects have been considered in the Canadian Arctic. Engineering studies conducted for these projects recognized the specific environment in which the proposed pipelines were to be located. A large volume of information and data describing the specifics of the Canadian Arctic environment has been collected. Different design approaches and concepts have been developed to address the design problems caused by the presence of continuous and discontinuous permafrost. A continuing evolution could be observed in understanding of the northern environment and development of associated design solutions.

The Interprovincial Pipe Line (NW) oil pipeline from Norman Wells, N.W.T. to Zama, Alberta differs from the previous projects in its design concepts, size and completion phase. The project consists of 868 km of 323 mm pipeline and has three pump stations and a design capacity of approximately 4800 m^3/day (30,000 bpd) of crude oil. Construction activities on the project were commenced during the winter of 1982-1983, and completion is scheduled for spring, 1985. The location of the pipeline route within the Northwest Territories and Northern Alberta is given on Figure 1. Crude oil cooling will only occur at Station 1 at Norman Wells, where the input temperature of the oil is approximately $-2^{o}C$.

The pipeline will be constructed during the winter season, and in general no permanent work pad will be employed. The minimum depth of cover is 0.76 m, with an additional construction tolerance.

FIG. 1 LOCATION OF NORMAN WELLS OIL PIPELINE

Design approaches and supporting analytical calculations that formed the basis of the design of this pipeline are discussed in this paper.

DESIGN CONCEPTS

Historically, pipelines were treated from the structural point of view as pressure vessels, with internal pressure being the dominant loading used to define the wall thickness and grade of the pipe. Early attempts to apply the same logic to the pipelines located in discontinuous permafrost resulted in the development of designs which were both complex and costly. These designs required placing the pipe on above ground supports, or creation of a local environment around the pipe that in essence duplicated the environment of pipelines located in the south.

Design concepts developed for the IPL (NW) oil pipeline differ signficantly from design concepts used for other Arctic pipelines. These differences can be summarized as follows:

- Location of a buried pipeline in permafrost will result in some degradation of permafrost and will cause differential settlement of the terrain. The magnitude of the differential settlement can be controlled and limited to an acceptable level by designing the pipeline in such a way that it will have a low energy input to the environment.

- The pipe is treated as a structural member that is designed to withstand deformations caused by differential settlement resulting from construction and operation.

- To the extent possible, the pipeline is located on previously disturbed and cleared rights-of-way (seismic cut lines, and telephone line).

The implications of applying the above design criteria to the IPL (NW) oil pipeline are described in this paper.

LOADING MECHANISMS ACTING ON A BURIED PIPE

For a general case of a buried pipeline, it is convenient to group loadings acting on the pipe in two broad categories:

- primary loadings
- secondary loadings.

By definition, primary loadings are loadings which are not relieved by deformation and/or which are not displacement limited. Conversely, secondary loadings are those which are relieved by deformation or which are caused by forces associated with limited displacement. For the purpose of illustration, internal pressure may be considered as an example of primary loadings, while temperature differential might be considered to cause secondary loadings.

From the above definition, it can be seen that a buried pipeline will be subjected to similar primary loadings independent of its location (in unfrozen terrain or degrading permafrost). A buried pipeline in degrading permafrost and subjected to differential settlement and/or frost heave will experience secondary loadings significantly different from those acting on a pipeline located in stable terrain.

Consequently, analytical efforts aimed at developing appropriate structural designs for a buried pipeline located in permafrost will be concerned with defining and evaluating the effects of the secondary type of loadings.

The most important secondary loadings affecting the design of a pipeline located in permafrost are the loadings caused by differential settlement, frost heave and seismic activity. These loading mechanisms are discussed in more detail below.

Internal Pressure and Temperature Differential

Operational loadings such as internal pressure and temperature differential are determined by the pipeline system, the ambient temperature during installation of the pipeline in the ditch, and the applicable codes and regulations. These loads include the specified internal pressure, the temperature differential, the pipe weight and other live and dead loads. The maximum allowable operating pressure within the pipeline system is 9929 kPa (1440 p.s.i.). Therefore for a selected nominal outside diameter and a specific minimum yield stress, the minimum nominal wall thickness may be determined. The hydrostatic test pressure required to prove strength is specified by the applicable regulations. For general cross country buried service, the minimum hydrostatic test pressure is 12,410 kPa (1800 p.s.i.).

The temperature differential is the maximum difference between the extremes of the operating temperature of the flowing oil, and the so called reference temperature. The reference temperature is defined as the thermally stress free temperature of the pipeline when laid in the ditch and backfilled. The reference temperature will therefore be at or near the ambient air and ground temperature at the time of installation and tie-in. The temperature differential utilized in this project was associated with either the maximum difference between the operational temperature. The actual temperature differential used for many of the design studies was 36°C (65°F). This corresponds to a reference temperature of approximately -30°C and the maximum operating temperature of +6°C. The reference temperature arises from the planned winter construction season.

The pipeline operating pressure would of course decrease from one station to the next, and certain sensitivity analysis were carried out to ensure that the high pressure case (9929 kPa), was indeed the more critical case for thaw settlement or frost heave analysis.

Thaw Settlement

As mentioned previously, the low energy input from the pipeline into the permafrost means that the pipeline will not directly cause significant thawing of the underlying permafrost. However, even though no permanent work-pad will be used, construction disturbance and clearing activities will cause the permafrost to thaw out slowly with time in many locations, because of the changed surface thermal conditions. If settlement were to develop uniformly, little or no effects would be felt by the pipeline resulting from this thawing. However, at changes in terrain conditions such as from bedrock to soil, from initially thawed to frozen ground, or at sudden changes in subsurface ice content, differential thaw settlement may occur over short distances. Because of the possibility of completely thawed stable soil existing close to a permafrost soil deposit that could settle to the maximum amount, the differential settlement across the transition was conservatively assumed equal to the total settlement that could occur within a terrain unit. This loading mechanism is illustrated on Figure 2. An "infinite" span length was generally considered, as this usually provided the worst case for the pipe conditions considered.

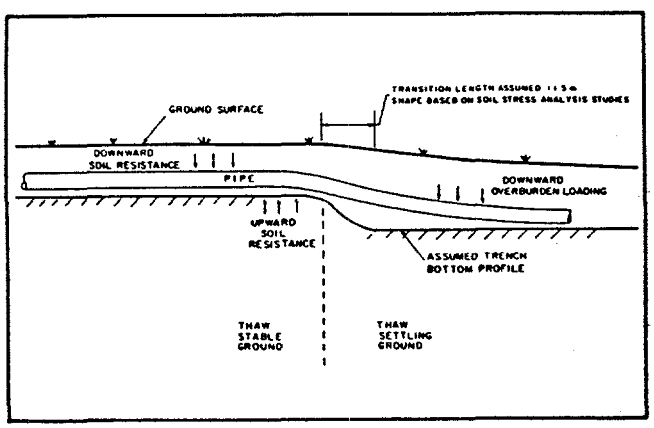


FIG. 2 DIFFERENTIAL THAW SETTLEMENT AT A TRANSITION

Based on a very extensive borehole data base, thaw settlement analyses were carried out between Norman Wells and the Zama Lake terminal (kmp 868). Computer programs were used to assess the thaw strain of different soil layers, and integrate these to obtain the thaw settlement occurring between the pipe base and the maximum anticipated depth of thaw. As the pipe base was to be located somewhere between 1.06 m and 1.3 m, and the maximum anticipated thaw depth in a 25 year period based on long term field observations was approximately 6 m below ground surface, the depth of soil which would thaw was well defined. The different terrain units encountered along the route included lacustrine soils with or without an organic cover, and glacial till deposits that could exhibit a variable depth of organic cover. In one area of the route to the south of Fort Simpson, thick peat deposits were also present, and these required a special treatment in the design process.

Several natural thaw settlement test sites were located along the route to observe thaw settlement based on changes in surface relief. These test sections were established where a cutline or right-of-way was known to have caused thawing of the permafrost, and the differential elevation in ground surface could be observed across the edge of the cutline between disturbed and undisturbed ground. In addition, several previous studies including sites in the Fort Simpson area visited by McRoberts et. al (1978) were examined to expand the data base for the pipeline route in this area.

Based on these thaw settlement studies, a design differential thaw settlement of up to 0.8 m in mineral subsoil deposits was established, depending on the location along the route. In general, thaw settlement was anticipated to decrease from north to south along the route. This is in response to a general decrease in ice content coupled with the general warming trend in mean ground temperatures. In addition, in the thick organic soil deposits between the Mackenzie River and Zama Lake a design differential thaw settlement of 1.2 m was adopted.

The loading mechanism at a thaw settlement transition involves downward loading by the soil within the thaw settling zone, and restraint to pipe movement within the thaw stable zone. In the thaw settling zone, the block of soil over the pipe, causes downward loading arising from two sources, namely (a) the effective weight of the soil block above the pipe; and (b) side shear along the sides of the block due to differential movement between the pipe and the surrounding settling soil. The side shear term was estimated based on the effective strength properties of the backfill soil. Within the thaw stable zone, a relatively conservative value was adopted for upward soil resistance on the thaw stable side of the transition. This could result from an unfrozen, competent till deposit which would provide support for the pipe as it crossed the transition. In addition, downward soil loadings would be exerted on the pipe on the thaw stable side of the transition, due to the soil above the pipe at this location. The downward loading in the thaw settling zone was anticipated to increase with increasing soil density, lower water table, and smaller thicknesses of organic soil cover. Reasonable combinations of soil density, thickness of organic cover and position of water table were used to arrive at representative design downward overburden loadings in the thaw settling zone. Conventional bearing capacity theory was employed to estimate the upward soil resistance in the stable zone.

These downward loadings due to thaw settlement subsequent to construction are unique and novel in pipeline engineering, and are not normally encountered in conventional pipelining practice.

Frost Heave and Pressure Dependency

It is not intended to operate the oil pipeline at temperatures significantly below 0^oC. However, a possibility exists that the pipe may induce small amounts of frost advance and heave beneath it. If the pipe traverses several kilometers of stable permafrost at temperatures of 1 or 2^oC below freezing on average, the contents of the oil pipeline will tend to adapt to the surrounding subzero temperatures. The ground temperature in a permafrost zone could fall as low as -8 to -10^oC in the middle of winter. Should the pipe pass from terrain underlain primarily by permafrost to unfrozen ground, it will tend to form a frost bulb of limited extent around the pipe in the unfrozen soil zone. Studies were carried out to show in general that the frost bulb would form a part of a larger layer of seasonal frost, and that the overall stiffness of the seasonal frost - permafrost transition would be sufficient to prevent excessive curvatures in the ground at the pipe location. This analysis involves studying the curvature of the ground at the transition between the permafrost and frost bulb, and is similar to that described by Nixon et al, (1983).

At stream crossings, however, and for some overland pipe locations, the pipe will be buried deeper in unfrozen soil at sag bends. The frost bulb around the pipe may not form part of the seasonal frost zone in these cases, and separate pipeline stress analyses were required to incorporate these effects into the pipe design. Sag bends were identified as being particularly acute areas for frost heave analysis, as upward pressure at the apex of a sag bend would increase the compressive strains in the pipe. These additional strains increase the compressive strains already present in the pipe due to temperature differential and internal pressure. Consequently, the frost heave potential of the soil beneath the pipeline was evaluated, and input parameters were provided to the stress analysis to indicate the additional strains imposed on the pipe by frost heaving across a frozen-unfrozen transition.

Seismic Effects

A buried pipeline is potentially subject to a range of loading conditions from several seismic hazards. The strong ground motions induced by a seismic event are characterized by a series of ground waves which can impose strains on buried pipelines. The additional straining imposed by seismic motions was considered in the design of the Norman Wells pipeline. No known active faults were identified in the Mackenzie Valley, therefore ground rupture due to faulting was not considered as a design issue for this route. Seismic accelerations were also introduced into the stability analysis for sloping terrain using Newmark's (1965) method for incorporating seismic acceleration into slope stability analysis. A review of available information indicated that the soils encountered along this route were not susceptible to liquefaction. The seismic design criteria for the Norman Wells pipeline were based on those laid out by Newmark (1974) and Hall and Newmark (1977). The concept of the design probable earthquake (DPE) and a design maximum earthquake (DME) was considered, as these encompass two levels of earthquake hazard. The lower level of hazard, the DPE, is associated with a return period for the design event of approximately 50 years and the higher event has a longer return period of 100 to 200 years.

In general, the impact of seismic aspects on the pipeline design was very minor, due to the relatively low level of historical seismic activity in the area.

Based on the recommendations of Newmark (1974), and subsequent updating by Hardy Associates (1978) Ltd., ground accelerations for the DME of 12 and 3% respectively were established for the two zones identified along the route, with associated velocities of 15 and 4 cm/sec. Using Newmark's procedure for obtaining pipe strains based on these values, strains of 2.5×10^{-4} and and 0.66×10^{-4} were established for unfrozen soils, and 1.25×10^{-4} and 0.33×10^{-4} were established for permafrost soil conditions within the two zones identified. These strains were reduced by 15% for the design probable earthquake event. Strains induced by seismic effects were considered additional to those arising from the other loading mechanisms outlined above.

DESIGN CRITERIA

Structural and geotechnical design criteria have been developed to place limitations on allowable stresses and strains in the pipe and acceptable amounts of differential settlement and frost heave.

Stress and Strain Criteria

Combined circumferential and longitudinal stresses computed on an elastic basis were limited to prevent excessive ductile yielding within the pipe. The maximum longitudinal compressive strains were limited to prevent local buckling of the pipe wall. The maximum longitudinal tensile strains were limited to prevent excessive tensile yielding in the pipe wall. These strains were computed using an inelastic analysis.

The stress limits used for the project are those dictated by the Oil Pipeline Regulations issued by the National Energy Board of Canada and CSA Standard Z183-M1982.

The maximum longitudinal tensile strain was limited to 0.5%. The maximum longitudinal compressive strain for a pressurized pipe was limited to -0.75%. For the design condition, 0.667 to 0.889 of the allowable strains were used for static loads, and for static plus seismic loads respectively. Local deformation (out of roundness) was limited to 5% of the outside diameter for construction loadings and 15% of the outside diameter for operational loadings.

Thaw Settlement

As mentioned above, detailed thaw settlement calculations and field observations were carried out to establish the likely total and differential thaw settlement along the pipeline route. These values were established to be 0.8 m within the first 78 km south of Norman Wells, 0.75 m in the region lying between 78 and 440 km south of Norman Wells, and 0.7 m for permafrost areas along the remainder of the route. In areas of thick peat, the design thaw settlement was taken to be 1.2 m. These are reasonable maxima for much of the terrain covered, but may not include occasional extreme amounts of thaw settlement at isolated locations. As outlined later, these will be identified by monitoring. Soil stress analyses accounting for soil arching and continuity across a thaw settlement transition indicated that the design settlement could occur over a distance in the range of 5 m or less. In view of the general lack of information on the development of differential settlement with distance, a transition length of 1.5 m was selected as a conservative distance over which the design settlement would develop.

For 0.76 m of cover, the downward soil loading in the thaw settling zone was assumed to be 3.65 kN/m (250 lb/ft) in the Northern part of the route, and 3.2 kN/m (220 lb/ft) for the area between 440 and 868 km south of Norman Wells. These values assume the presence of loose inorganic and organic soils in the ditch backfill over the pipe. The downward soil loading on the thaw stable side was assumed to be twice the values outlined above for the soil loadings exerted on the pipe by the softer soils on the thaw settling side. Greatly reduced soil loading values were also considered for the pipe when carrying out the thaw settlement analysis in thick peat stratigraphy.

Frost Heave

The ground temperatures within a stable permafrost deposit were analyzed to obtain the anticipated oil temperature for frost heave analysis. The flowing oil temperature was assumed to be equalized with the ground temperature at burial depth in stable permafrost. When the pipe passed from frozen to unfrozen ground, it was assumed that these temperatures were imposed directly on the outer surface of the pipe causing the growth of a frost bulb beneath the pipe. A two-dimensional geothermal simulation was then carried out to determine the growth of the frost bulb around the pipe using the Hardy Associates (HAL) geothermal simulator, as described by Nixon and Halliwell (1982). Typical results for this analysis are shown on Figure 3.

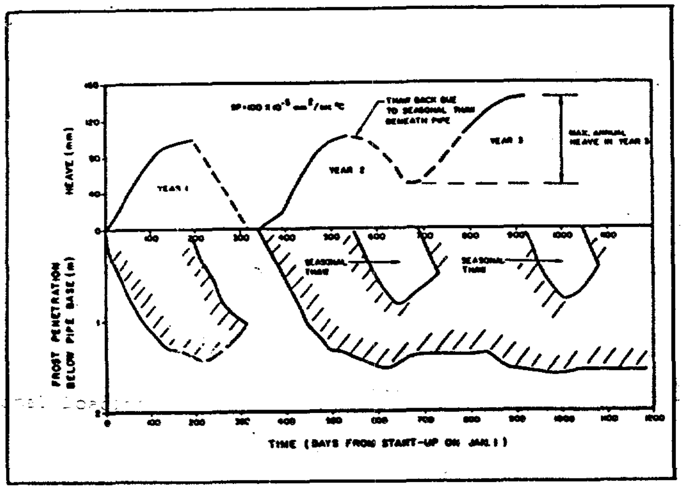


FIG. 3 FROST DEPTH AND HEAVE PREDICTION

Knowing the depth of frost advance beneath the pipe, and the thermal gradient at the frost line, an analysis of the amount of frost heave was carried out. This was completed using the frost heave theory of Konrad and Morgenstern (1982), and the hand integration method described by Nixon (1982). The frost heave properties of Calgary silt were adopted to provide a reasonably conservative estimate of frost heaving in the fine-grained soils along the route. This material is known to be highly frost susceptible, displays a high segregation potential, and has been subject to intensive study by many researchers for several years. In addition, further calculations were carried out to indicate the pressure dependency of frost heaving. This was required later when carrying out stress analysis on the pipeline, to provide the relationship between pipe heave and increased pressure exerted by the pipe.

The predicted frost heave experienced by the pipe at normal overburden pressures varied between 125 mm (4.9 inches) to 97 mm (3.8 inches) depending on the location along the pipeline route. This maximum frost heave was usually experienced during the second or third year of operation, as the pipe usually experienced a lesser amount of frost heave in the first year. In later years, the equilibrium frost depth achieved in the second or third was not exceeded. Further analyses were carried out to indicate the beneficial effects of 5 cm of urethane insulation wrapped around the pipe. This indicated that in the more northerly regions, the frost heave beneath an insulated pipe could be reduced to 79 mm (3.1 inches) and further south could be reduced to 63 mm (2.5 inches). Predictions of frost heave for increased pressure caused by pipe bending or soil pipe interaction effects indicated that the design amount of frost heave could be reduced by about 1/2 if the average pressure on the frost bulb were increased by about 100 kPa.

The shape of the frost heave transition, or alternatively the rate at which the frost heave across the transition develops is an important parameter in the stress analysis. Clearly, if the frost heave is assumed to develop suddenly at a transition, thereby creating a sudden step increase in the elevation of the pipeline trench base, this will provide for the most conservative or extreme pipe curvatures and strains. This is likely too conservative, as frost heave is liable to develop over some short transition length, even though the soil type change is sudden. For these studies, the frost heave was assumed to develop over a transition 1.5 m in length. This was based on geothermal analysis showing that the frost bulb would join gradually onto the vertical permafrost interface, and would not adjoin it suddenly at right angles.

GEOTECHNICAL INPUT TO STRESS ANALYSIS

Load Displacement Relationships

Load displacement relationships were required by the pipeline stress analysis to model the interaction between the pipe and the surrounding soil. This was the case for analysis of both thaw settlement and frost heaving conditions. Where the ground was unfrozen, conventional bearing capacity theory was used for a 0.3 m wide "footing" to obtain the ultimate yield point of the pipe reacting against the soil. However it is also necessary to estimate the pre-yield displacements. For simplicity, the soil was assumed to yield in an elastic-plastic manner. Consequently, the pre-yield deformations could be presented by a spring constant, K, and the relationship between load and deformation was assumed to be

$$P = K \cdot y \quad \text{for } y \text{ less than } y_f,$$

and $$P = P_{ultimate} \quad \text{for } y \text{ greater than } y_f.$$

where P = load per unit length of pipe,
y = pipe displacement, and
y_f = pipe displacement at soil yielding.

Of considerable importance was the upward soil resistance in the thaw stable side for the thaw settlement analysis. Conventional bearing capacity theory indicated that load of up to 175 kN/m (12 kips/ft) could be exerted on a 0.3 m wide pipe bearing on a competent till deposit. This value could be considerably lower in the softer lacustrine silt clays, and was generally thought to be a reasonable bound for this parameter. The pre-yield displacement was computed based on conventional elastic theory, and provided a pre-yield spring of 5750 kPa (120 kips/ft^2). As the edge of the transition was approached, the ultimate yield point of the soil was assumed to decrease to approximately 50% of its nominal value on flat terrain. This is due to the reduction in bearing support resulting from the loss of horizontal ground support in the longitudinal direction. The rate at which this reduction in ultimate pipe load occurs is a function of the pipe diameter, but for this situation the reduction in ultimate soil support was assumed to occur over a distance of 1.2 m from the crest of the thaw settlement transition.

Gravity Loading in Thaw Settling Zone

As mentioned earlier, the downward (gravity loading) on the pipe in the thaw settling zone was computed based on the effective weight of soil over the pipe coupled with the side shear exerted between the soil prism and the surrounding settling R.O.W. This is shown schematically in Figure 4. This is the most important parameter in the thaw settlement analysis, as it is the basic loading mechanism on the pipe. Strains and curvatures in the structure will ultimately be strongly dependent on this value. For a reasonable combination of position of the water table, thickness of organic cover, and density of the mineral soil, downward gravity loadings for different segments of the pipeline route were calculated and input to the stress analysis. Additional loadings due to the weight of pipe, contents and possible buoyancy weighting requirements were then included.

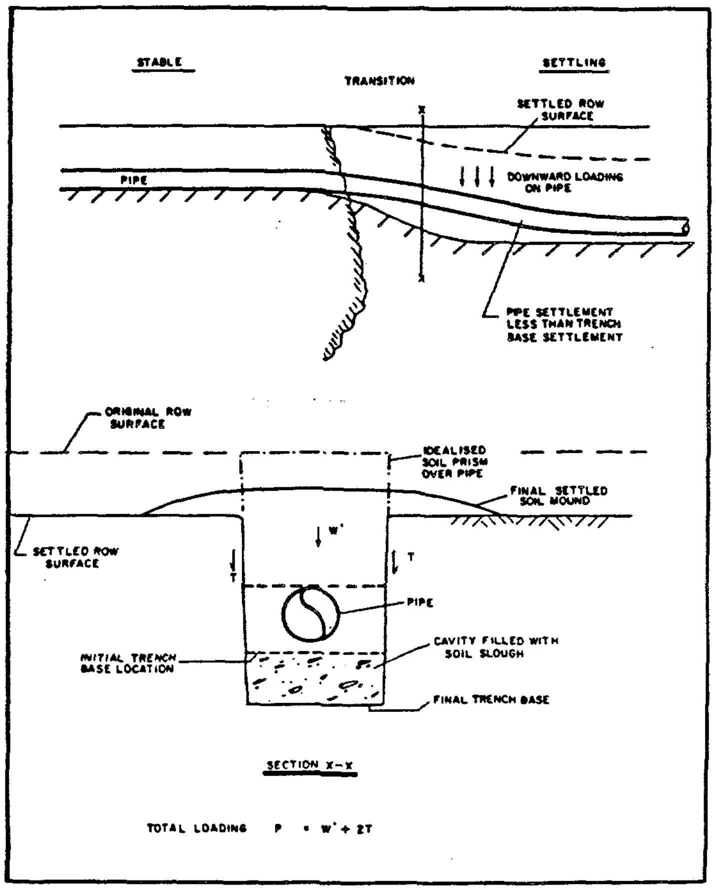


FIG. 4 ILLUSTRATION OF DOWNWARD (GRAVITY) LOADING OF PIPE IN THAW SETTLING ZONE

Uplift Resistance for Frost Heave Analysis

The resistance of the frozen soil in the stable permafrost is an important input to the frost heave analysis. This was analysed using two different possible modes of yielding of the pipe in the frozen soil, namely (a) viscous creep of the pipe upwards through the frozen soil, and (b) an analysis assuming no tension in the frozen soil and upward flexure of two frozen soil "cantilevers" adjacent to the pipe. These are illustrated on Figure 5. The former method was similar to the procedure outlined by Nixon (1978) for the design of strip footings on permafrost. The second procedure is a new analysis which sums the two components of the uplift resistance, i.e. the weight of the soil "blocks" over the pipe together with their flexural resistance to upward movement. There exists a minimum, or optimum uplift resistance for a certain width of the horizontal cracks extending out from the pipe.

Both analyses converged on a similar answer, and the uplift resistance was calculated to be in the range of 220 kN/m (15,000 lbs/ft), assumed to be mobilized at a yield displacement of 5 mm (0.2 inch). This elastic-plastic idealization of a rather more complex viscous behaviour of frozen soil was used to represent the resistance of the frozen soil to upward pipe motion.

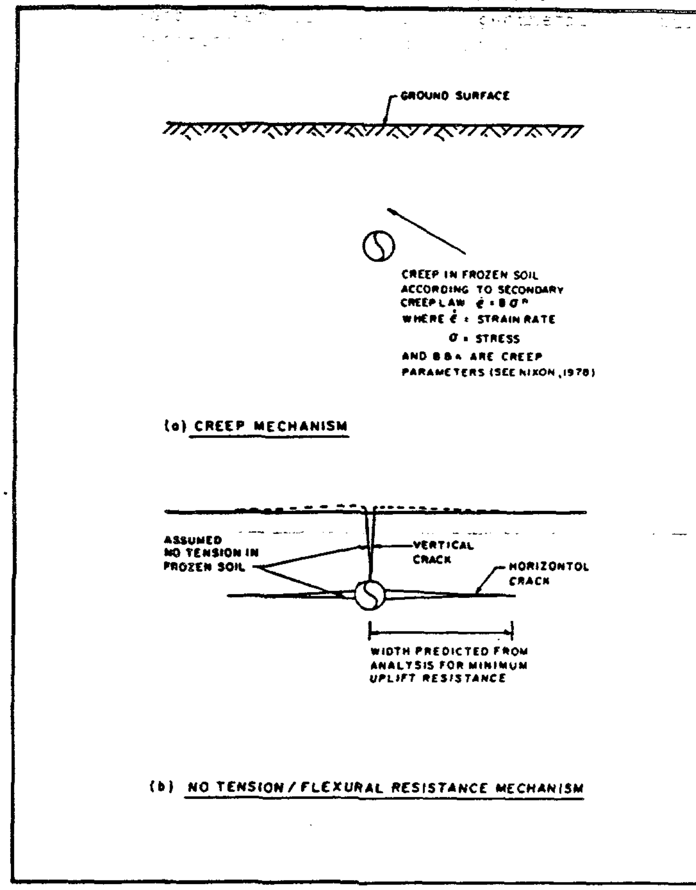


FIG. 5 METHODS OF COMPUTING UPLIFT RESISTANCE IN FROZEN SOIL

Localized Loadings on the Pipe

Should the pipe trench encounter a boulder immediately beneath the trench base, and thaw settlement occurs subsequently adjacent to the boulder location, a concentration of stresses might occur in the pipe supported on the "point load" provided by the boulder. Stress analysis will show that a concentrated load of a large enough magnitude would cause denting of the pipe. A geotechnical analysis was carried out to indicate the magnitude of the loading which could be exerted by a large cobble or boulder embedded in a soil matrix. Details of this analysis are beyond the scope of this paper, but it is sufficient to say that for boulders up to a size of 0.15 to 0.3 m, the cobble or boulder would tend to punch into the soil and not cause significant increases in stress at the base of the pipe.

However, boulders larger than this size would become a support point for the pipe, and it was necessary to carry out a stress analysis to indicate whether local denting or ovalling of the pipe would occur. Boulders and cobbles will tend to occur in terrain units underlain by glacial till deposits, and the possibility of overexcavation by overblasting or deeper ditching might be considered to create a layer of loose bedding between the pipe base and the underlying undisturbed till. In this way, the presence of a boulder in the competent till matrix would not present so severe a problem, as the stress transfer between the boulder and the pipe would be lessened. Geotechnical studies showed that a thickness of loose bedding in the range of 0.15 m thick beneath the pipe would reduce the soil stresses and pipe strains significantly below those normally encountered in the competent boulder-free till deposit.

STRESS ANALYSIS

The assessment of the geotechnical information developed as a basis for the stress analysis confirmed the basic design concept that the parameters of the pipe (grade and wall thickness) will be governed by the required structural response of the pipe to the secondary-type loadings caused by differential settlement and frost heave. The stress analysis was carried out using the three-dimensional finite element computer program "SAVFEM" (Structural Analysis Via Finite Element Method), as described by Workman (1977). For example, the thaw settlement problem has been idealized as shown on Figure 6.

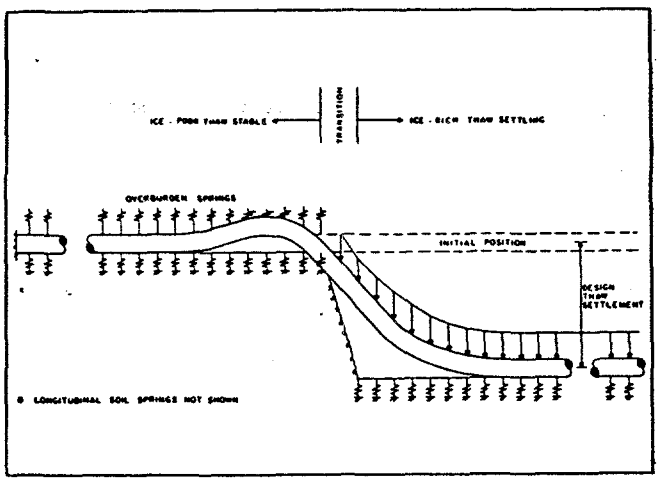


FIG. 6 BASIC FINITE ELEMENT MODEL FOR THAW SETTLEMENT CALCULATION

Method of Analysis

The analysis carried on for the project involved the following basic steps:

- sensitivity runs aimed at development of an appropriate model
- development and finalization of the model
- design and sensitivity runs aimed at finalizing the pipe parameters.

The above approach was used for development of models and design calculations for both differential settlement and frost heave studies.

Sensitivity runs were carried out to assess the impact of input parameters and data on the results of the analysis. The information so generated was used to develop a generalized model, which was then used to evaluate design solutions for the differential settlement and frost heave problems.

Development of the generalized model included establishing the size of finite elements for different sections of the model and selection of the type and number of the bi-linear "springs" used to represent the interaction between the pipe and soil.

Finally, design and sensitivity runs have been completed for loading combinations defined for different regions along the proposed pipeline route.

Cases Studied

The basic reasons used for selection of cases within the scope of the stress analysis were (a) to enhance the understanding of the impact of the different input parameters on the results of the analysis; (b) to develop a representative model or models to be analyzed in detail; (c) to complete a parametric study of variables, and; (d) to complete a series of design-type analyses. The following problem areas have been analyzed in detail: (i) differential pipe settlement; (ii) frost heave; (iii) localized denting caused by large bounders, and (iv) bends.

In addition to the above problem areas, a study was conducted on the beneficial effects of the hydrostatic testing of the line using warm water.

Selected Results

The length of this paper precludes a systematic review of the results of the stress analysis and its impact on the design solutions accepted. The following are the essential results:

- the depth of cover over the pipeline strongly affects the loading on the pipe subjected to differential settlement. Considering the location of the proposed pipeline in a remote area, the minimum depth of cover was reduced to 0.76 m from the 1.0 m required by the oil pipeline regulations of the National Energy Board of Canada (NEB).

- the magnitude of frost heave predicted for the bare pipe at stream crossings cannot be accommodated by reasonable increases in the wall thickness of the pipe. The amount of the frost heave in such areas has to be controlled through the use of thermal insulation.

- the wall thickness of the pipe required to withstand the anticipated amount of differential settlement for the specified downward loads is shown in Table 1. These wall thicknesses should be compared with the wall thickness of 6.22 mm (0.245 inch), based on the elastic circumferential stress limit ignoring secondary loadings such as frost heave or thaw settlement.

TABLE 1

DESIGN WALL THICKNESS FOR SPREADS 1, 2 AND 3
GRADE 359 MPa (52 ksi) (0.76 m of cover)

Design Spread	kmp	Seismic Zone	Case	Design Thaw Settlement mm (in)	Soil Loading Thaw Stable/ Settling Side kN/m (lbs/ft)	Design Wall thick mm (in)	Operating Strain of 0.5% Temp. Diff. °C (°F)	Max. Axial Strain (%) (*)
1	0- 78 kmp	A	A	.80 (32)	7.3/3.7 (500/250)	7.16 (.282)	36.1 (65)	.497
2	78-440 kmp		B	.75 (30)	7.3/3.7 (500/250)	6.91 (.272)	36.1 (65)	.496
3	440-478 kmp		C	.70 (28)	6.4/3.2 (440/220)	6.35 (.250)	36.1 (65)	.499
	478-868 kmp	B	D	.70 (28)	6.4/3.2 (440/220)	6.35 (.250)	36.1 (65)	.499

Note: ( ) Max. Allowable Strain
(*) DME and DPE earthquake not included.

Wall thickness ignoring frost heave or thaw settlement was 6.22 mm (0.245 inch), based on the elastic circumferential stress limit of 72% of the specified minimum yield strength.

- localized denting caused by the presence of large boulders within the transition zone of settling pipe did not exceed 15% of the diameter of the pipe.

- strains at the pipe bends caused by pressure and temperature differential were below the criteria set for the project.
- hydrostatic testing of the line using warm test medium to pressures approaching or reaching the pipe material specified minimum yield strength (SMYS) has the effect of increasing the reference installation temperature and correspondingly reducing the temperature differential.

CONCLUSIONS

Confirmation of the Validity of Design Concepts

The analysis completed for the proposed IPL (NW) oil pipeline from Norman Wells, N.W.T. to Zama, Alberta confirmed both the technical validity and economic attractiveness of the design concepts proposed.

Specifically, it became apparent that significant economic benefits and simplification of construction procedures can be achieved by designing a pipeline with adequate structural strength such that it can withstand, without structural damage, the combination of loadings that it will be exposed to as a result of loadings created by the operating parameters (pressure and temperature), and environmental forces.

Other analyses not described in this paper confirmed the validity of the concept of limiting the thermal effect of the pipe on the permafrost by designing a low-energy pipeline located, where possible, on already disturbed terrain.

Monitoring and Observation During Operation

It is planned to select typical locations where frost heave or thaw settlement might occur and carry out observations and monitoring during the post-construction phase. This will involve installing temperature instrumentation and vertical risers on the pipe to monitor both frost heave and thaw settlement, and the resulting curvatures experienced by the pipe at these locations. Some of the areas will include sag bend locations, where insulation around the pipe will be used to mitigate frost effects at these locations. Strain gauges will also be used to monitor strains in the pipe at the potential heave sections.

The effects of thaw settlement will be monitored by visual observations along the route at several times during the initial years of operation. As the design thaw settlement is in the range of 0.7 to 0.8 m, and the pipeline is designed to safely accommodate settlements of this magnitude, it is apparent that settlements will become clearly visible before a problem develops with excessive pipe strain. Settlements of this order can be readily observed by an engineer walking the line, or flying the route at low altitude. Regular observations will constitute the most important aspect of monitoring to anticipate thaw settlement problem areas. Areas delineated by these visual observations will be subject to further scrutiny, and will be flagged as areas for possible maintenance.

ACKNOWLEDGEMENTS

The authors wish to express their sincere thanks to colleagues at Interprovincial Pipe Line (NW) Ltd., Hardy Associates (1978) Ltd., and Canuck Engineering Ltd. In particular the results of many discussions with Prof. N.R. Morgenstern of the University of Alberta, Dr. G. Workman of Stresstech Ltd. and Dr. W. Slusarchuk of Hardy Associates are reflected in the results given in this paper. Dr. E. McRoberts of Hardy Associates contributed in the areas of seismic design parameters, and Mr. John Tse of Canuck Engineering and Ms. Susan Nelson of Stresstech Ltd. carried out the pipe stress analyses. In addition, the authors wish to sincerely thank Mr. W. Pearce of Interprovincial Pipe Line (NW) Ltd. for permission to publish the results of this paper.

REFERENCES

Hall, W.J. and Newmark, N.M. Seismic Design Criteria for Pipelines and Facilities, Proc. Lifeline Earthquake Eng. Spec. Conf., ASCE, 1977, pp. 18-34.

Konrad, J.M. and Morgenstern, N.R. Effects of Applied Pressure on Freezing Soils, Can. Geotech. J. 19, 1982, pp. 494-505.

McRoberts, E.C., Law, T.C. and Moniz, E. Thaw Settlement Studies in the Discontinuous Permafrost Zone, Proc. 3rd Intl. Permafrost Conf., Edmonton, Alberta, 1978.

Newmark, N.M. Effects of Earthquakes on Dams and Embankments, Geotechnique, 15. No. 2, 1965.

Newmark, N.M. Seismic Design Criteria for Canadian Arctic Gas Study Ltd., A report prepared for Northern Engineering Services Co. Ltd., Calgary for Natural Energy Board Hearings, 1974.

Nixon, J.F. First Canadian Geotechnical Colloquium: Foundation Design Approaches in Permafrost Areas, Can. Geotech. 15, No. 1, 1978, pp. 96-112.

Nixon, J.F., Morgenstern, N.R., and Reesor, S. Frost Heave Pipeline Interaction Using Continuum Mechanics, Can. Geotech. Journal 20, 1983, pp. 251-261.

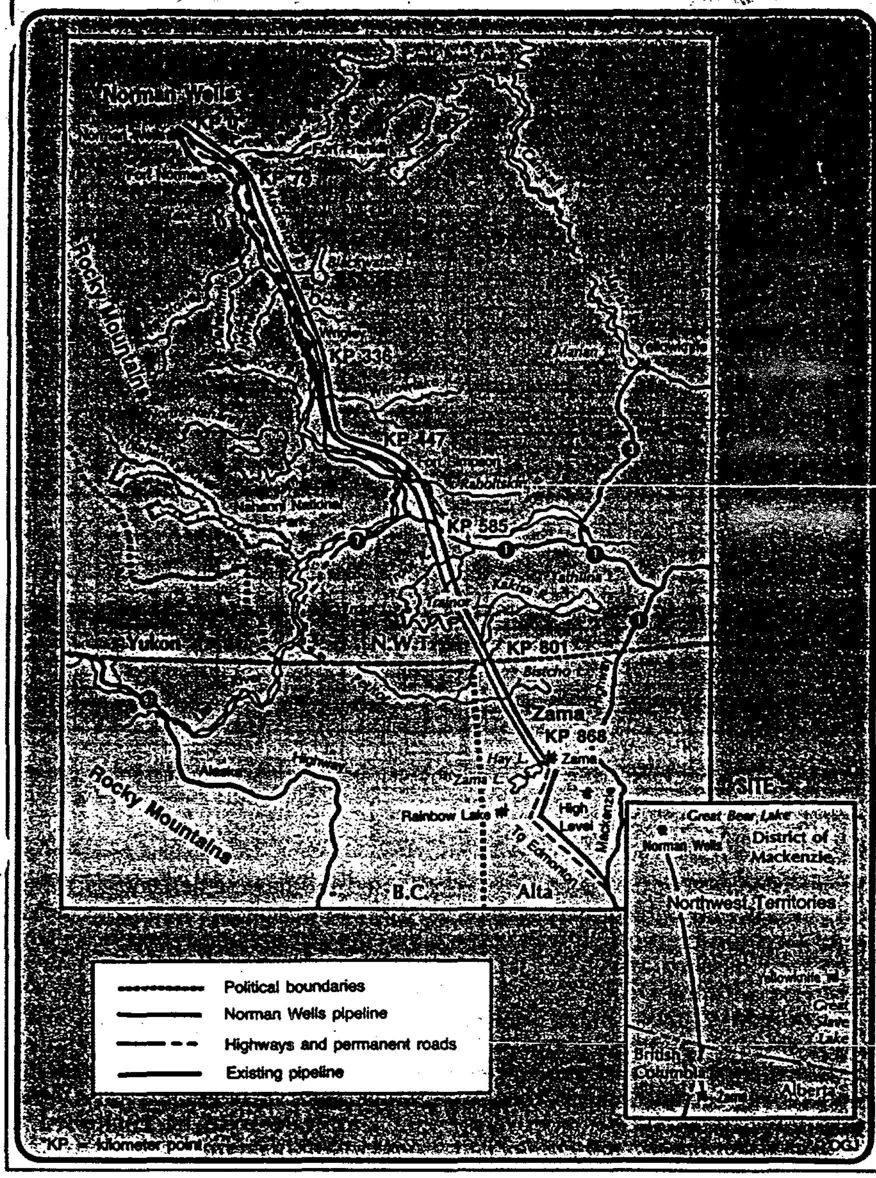
Nixon, J.F. Practical Applications of a Versatile Geothermal Simulator, Proc. J. of Energy Resources Technology, Am. Soc. Mech. Engineers, in press, 1983.

Nixon, J.F. Field Frost Heave Predictions Using the Segregation Potential Method, Can. Geotech. J. 19, 1982, pp. 526-529.

Workman, G.H. Development of a Fully Coupled Inelastic Straight Pipe finite Element, Proc. 6th Canadian Congress of Applied Mechanics, June, Vancouver, B.C., 1977.

Fig. 1

Major step in sub-arctic pipelining



territorial government departments in resource development in the Canadian north. This familiarity allowed him to ease the project through the complex regulatory framework which required more than 400 permits of licenses and obligated IPL (NW) to continuing public participation.

Schedule. Construction of the Norman Wells Pipeline took place over the course of 3 years, with mainline construction being done during the winter months. The project was completed during 2nd quarter 1985. The master schedule is shown on Fig. 2.

Because of the nature of the terrain, active travel on the land was restricted to the winter months. In the Northwest Territories, travel on the land, without all-weather roads, is prohibited after April 1 and April 15, south and north of 64°N, respectively.

For planning and contractual purposes the pipeline route was divided into six construction spreads. Based on land use restrictions, construction schedules called for construction of pipeline spreads 1, 4, and 6 during 1984 and spreads 2, 3, and 5 in 1985.

Actual construction commenced in January 1983 with right-of-way clearing on spreads 1, 4, 5, and 6. Development of numerous construction facility sites such as stockpiles, barge landings, camp sites, and borrow sites was started during the winter of 1983.

In January 1984, mainline construction started on spreads 1, 4, and 6. By spring breakup, 587 km of pipe had been laid. Work on the balance of mainline was executed using two construction spreads completing all work by Mar. 20, 1985. Pump station and operation and maintenance facilities were constructed during the summer of 1984. One remote maintenance base was constructed at km 731 during winter 1985.

Transportation. Planning and execution of a pipeline project is an exercise in logistical planning. This was particularly true for the Norman Wells pipeline. Transportation realities imposed constraints on lead time for design and procurement to allow 1985 start-up schedule to be met.

The Alberta highway system and the Mackenzie Highway provide year round all-weather access adjacent to the pipeline route north to Fort Simpson, limited by the crossing of the Liard River which is served by ferry in summer and ice bridge in winter.

Highway travel to the pipeline route north of Fort Simpson is limited to a winter road which is usually open from mid-January to the first of April.

Travel on the Mackenzie Highway north of Fort Simpson during the summer is restricted by the absence of bridges on the Mackenzie River, Willowlake River, and minor streams.

Railway access to the pipeline is available through Hay River and Enterprise, N.W.T., and Meander River, Alta., via the Northern Alberta Railway.

Barge transportation to the pipeline route near Fort Simpson and north is available from Hay River, N.W.T., from June 15 to October 31.

Air service is available in proximity to the pipeline by scheduled air carriers to Rainbow Lake, Alta., Ft. Simpson, Wrigley, and Norman Wells. In addition, a community strip is available at Fort Norman.

Regulatory process

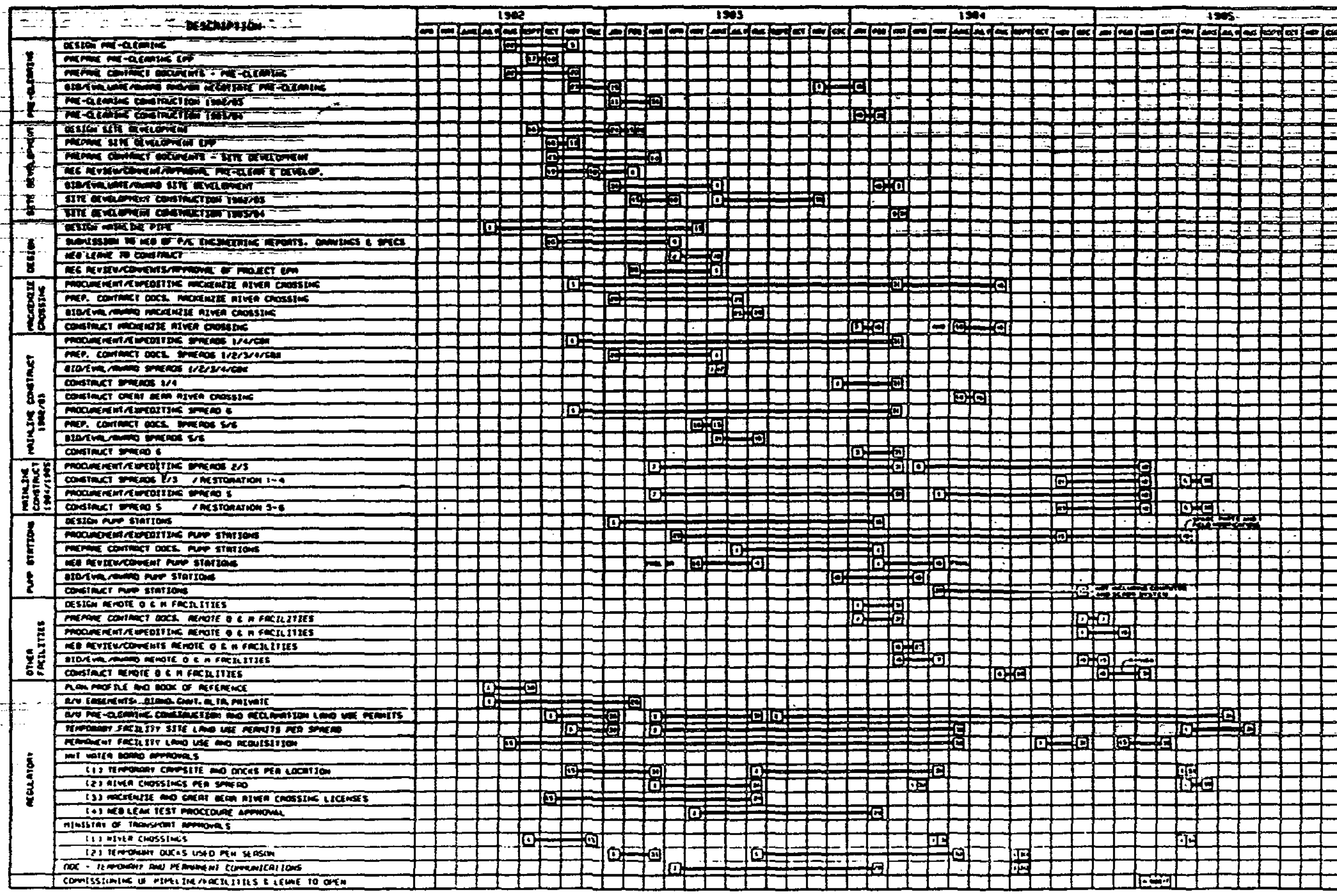
The Norman Wells pipeline crosses only Crown lands, some of which are subject to native land claims.

In the Northwest Territories, the lands involved are under federal administration by Indian and Northern Affairs Canada (INAC). Short sections near Norman Wells and Fort Simpson are administered by the Government of the Northwest Territories (GNWT).

Crown lands in the Alberta segment are administered by the Department of Energy and Natural Resources (DENR) of Alberta.

In 1979, plans by Esso Resources to expand the Norman Wells oil field prompted a detailed impact assessment. Public hearings were held by a Federal Environmental Assessment and Review Office (FEARO) panel. These hearings resulted in a set of environmental recommendations for consideration by regulatory agencies.

In 1980, IPL submitted an application to the National Energy Board (NEB) for authority to construct and operate the Norman Wells pipeline. Under the authority of the National



Construction schedule for Norman Wells pipeline project (Fig. 2).

Energy Act, the NEB conducted public hearings into the application.

In 1981, the NEB granted a Certificate of Public Convenience and Necessity allowing IPL to construct and operate the pipeline. This approval was subject to the fulfillment of certain conditions relating to the planning and design of the pipeline.

Included in the requirements of the NEB certificate were requirements for the completion of various engineering, environmental, and socio-economic studies, and review by intervenors. In June 1983, those studies were completed to the satisfaction of the NEB which issued "Leave to Construct" authorizing IPL to proceed with construction.

Following issuance of the NEB Certificate in 1981, IPL had entered into negotiations with government agencies having jurisdiction for easement agreements providing right of access and occupancy for lands.

In respect of federally administered lands, an Easement Agreement was negotiated with INAC. A companion Environmental Agreement containing environmental and socio-economic covenants was signed concurrently with INAC.

For Crown lands administered by the GNWT, an Easement Agreement was signed containing environmental and socio-economic covenants.

In Alberta, the right of access and use of land for the pipeline was provided by a pipeline agreement (PLA) negotiated with the DENR.

In addition to these major agreements, IPL has received about 400 licenses, permits, authorizations, exemptions, agreements, amendments, and consents provided for under various federal, territorial, and provincial statutory requirements.

Construction and operation of the Norman Wells pipeline is regulated by the Oil Pipe Regulations administered by the NEB. An inspection staff of the NEB was on site during construction to ensure compliance with the requirements of the regulations and certificate.

Inspectors representing the Department of Indian and Northern Affairs, the GNWT, the Department of Fisheries and Oceans, and the Province of Alberta were on site periodically to monitor for compliance with various permits, licenses, and authorizations.

System design

For the first fully buried oil pipeline in permafrost, design concepts were developed to limit thermal inputs to the environment and to increase the pipe strength. This strength was needed to provide for additional loadings caused by thaw settlement.

Frost heave loadings considered in the design included pressure, temperature differential, thaw settlement, frost heave, and seismic loads.

The properties of Norman Wells crude allow the oil to be pumped easily at $-2°$ C. Discharging oil at this temperature at Norman Wells allows oil temperatures to be controlled to ground temperature.

Geotechnical aspects. Location of the pipeline in an area of discontinuous and intermittent permafrost presented some extraordinary design problems including thaw settlement, frost heave, and slope stability.

Thaw settlement. Although care was taken to minimize land disturbance, clearing and construction caused the permafrost to degrade. Studies for this project determined that for rights-of-way which were cleared and subsequently undisturbed, the depth of thaw would be in the range of 1 to 4 m at 25 years. Subsequent grading or similar disturbance, would increase the depth of thaw to 4.5 to 6.5 m at 25 years.

This disturbance of permafrost in areas of discontinuous or intermittent permafrost can result in differential settlement across transitions. On the basis of an extensive examination of borehole data and thaw settlement

ANNUAL PIPELINE REPORT

Welding on the Norman Wells pipeline employed two crews for each of the projects' six spreads. Construction was mainly in the winter months over 2 years' time.

About this report...

This annual OGJ Pipeline Report focuses on recent major construction projects and innovations in metering and flow modelling. Details of Interprovincial Pipeline Ltd.'s Norman Wells pipeline, the first northern Canadian crude-oil line, focus on the construction of this first fully buried crude-oil pipeline in a permafrost environment. And a chronicle of the conversion of the Texoma crude line to natural-gas service emphasizes the role of federal and state regulatory agencies in such a project. Further, an innovation in metering high-pressure gas is evident in a Dutch project using a piston prover calibrated for ethylene metering. Finally, liquid accumulation and severe, terrain-induced slugging can be modelled and predicted with calculations offered in another article.

Pipeline in Canada's far north in service

A. R. Pick
J. D. Smith
Interprovincial Pipe Line (NW) Ltd.
Edmonton

Interprovincial Pipe Line (NW) Ltd. (IPL) in late 1984 completed construction of the first fully buried oil pipeline in permafrost terrain. The pipeline runs from Norman Wells, N.W.T., to Zama, Alta., (Fig. 1) transporting crude oil from the expanded oil field at Norman Wells.

Consisting of 868 km (520 miles) of 323 mm (12.7-in.) pipeline and three pump stations, the system is designed to transport up to 4,800 cu m/day (30,000 b/d). Throughputs can be increased by the addition of three more pump stations.

Although officially opened May 16, the pipeline was placed in service in April, 3 months ahead of schedule and at a cost of about $360 million (Can.) compared to an original project estimate of $576 million.

Pipeline setting

The Norman Wells pipeline was built in a region classified as sub-Arctic, characterized by long, cold winters and short warm summers.

In January, the coldest month, temperatures average between −25° C. and −30° C.; lows of −40° C. are common. Snowfall accumulation averages between 1 and 1.5 m. Minimum winter daylight hours vary from 3 hr at Norman Wells to 6 hr at Zama.

Summer is characterized by hot dry long days with only 2 to 3 hr of full darkness during early July.

For 526 km south of Norman Wells, the pipeline follows the Mackenzie River. The terrain is rolling with numerous valleys and high flat terraces. Well drained areas are covered in pine, white spruce, poplar, and aspen. Poorly drained areas are covered in black spruce and tamarack.

South of the Mackenzie River to Zama, the route is generally flat and poorly drained. The area is dominated by open coniferous forests of dwarfed black spruce and tamaracks with intermittent, significant areas of bog and fens.

Permafrost occurs over a very large proportion of the pipeline route. The permafrost is discontinuous, varying in depth from 50 m near Norman Wells to scattered patches 1 m thick near Zama. The active layer varies from 1 m or less near Norman Wells to up to 3 m near Zama.

The permafrost distribution (Table 1) includes discontinuities estimated by geophysical survey.

Many of the slopes over the length of the pipeline route were identified as sensitive on the basis of soil type, permafrost content, and degree of slope. Over 150 slopes were examined and subjected to the specific design treatment.

Along the Mackenzie River, the pipeline crosses approximately 160 identifiable drainages ranging from intermittent streams to a major crossing of the river itself.

Eleven streams are crossed that are classified as navigable waters under the Navigable Waters Protection Act. The Mackenzie River and the Great Bear River are considered as major crossings.

Table 1

Permafrost distribution along route

Section of line	% Frozen	No. of discontinuities
0-150 km	84	259
150-270	66	513
270-380	69	342
380-528	32	592
528-696	16	532
696-868	35	1,708

Table 2

Slope design guidelines*

Soil type	No mitigation required	Mitigation required: Slope treatment	Mitigation required: Select backfill†
Ice-rich clay	<9° stable	>18° Cut and insulate	>4°
Ice-rich till	<13° stable	>20° Cut and insulate	>7°
Ice-poor till	<18° stable	>18° Cut back depending on height	>10°

*13-m cleared width.
†On certain slopes where excavation was achieved with a wheel ditcher, the cut off angles for select material were increased.

Table 3

Design wall thickness*

Location, km	Design thaw settlement, m	Design W.T., mm
0-78	0.80	7.16
78-440	0.75	6.91
440-478	0.70	6.35
478-868	0.70	6.35
River crossing	—	9.54

*Pipegrade 359 kilopascals.

Management

Owner and operator of the Norman Wells Pipeline is IPL whose staff managed and directed construction and currently operates the pipeline.

Organization. Project management was divided into mission-oriented functional groupings.

Technical services management. The principal role of technical services management (TSM) was the planning and design for the project through IPL's Edmonton office.

Qualified consultants were engaged by IPL to perform the detailed pipeline design including stress analysis, geotechnical studies and design, environmental studies and design, pump station design, cathodic protection system design, communication and SCADA system design.

Construction services management. To facilitate procurement of material and construction, contractors' services, cost control, management, and inspection during construction, IPL appointed a construction services manager (CSM).

CSM services were provided by a joint-venture company formed by UMA Engineering Ltd., Canuck Engineering Ltd., and Hardy Assoc. (1978) Ltd. under the name of UMA-Canuck-Hardy. Operating from a home office in Edmonton, CSM provided procurement, project cost accounting, and field engineering services.

A field staff of up to 150 inspectors was organized to provide quality control during construction. IPL contracted with independent radiographic inspection firms to provide 100% radiographic examination of welds.

Furthermore, IPL had an audit of weld quality and radiographic interpretation conducted by another independent group. Another firm performed an internal pipeline survey.

Northern benefit management. During planning of the pipeline, IPL made commitments concerning the types and levels of socio-economic benefits to northerners and communities directly affected by the pipeline. Specifically the company reserved $61.5 million to firms operating in northern Canada with $10.1 million going directly into the communities adjacent to the right-of-way. IPL has exceeded those commitments, expending $74 million with $32 million going directly into the communities.

Northern relations management. Recognizing the significant government presence in the Northwest Territories and the high level of public participation in decision making, IPL established an office in Yellowknife.

Its manager was familiar with the highly integrated roles of federal and

GEOTHERMAL CONSIDERATIONS FOR
WOOD CHIPS USED AS PERMAFROST SLOPE INSULATION

By:

E.C. McROBERTS*, J.F. NIXON*

A. HANNA* and A.R. PICK+

Submitted to:

THE FOURTH INTERNATIONAL SYMPOSIUM

ON

GROUND FREEZING

August 5-7, 1985

Sapporo, Japan

* Hardy Associates (1978) Ltd.

+ Interprovincial Pipe Line (NW) Ltd.

ABSTRACT

The recent construction of the Interprovincial Pipe Line from Norman Wells, N.W.T. to Zama, Alberta required special design measures where the pipeline was buried in the ice rich permafrost slopes. To maintain the integrity of such slopes during subsequent pipeline operations, it was necessary to limit the amount of thawing. The insulation mode that was selected to meet design objectives specified the placement of wood chips on critical slopes after burial pipeline.

Background geothermal analysis and field data were considered to provide the depth of thermal degradation on disturbed terrain segments. A review of information on wood chips was carried out, including bacteriological decay aspects, leading to heat generation and loss of wood substance. Laboratory data on thermal conductivity, volumetric heat capacity and density for both new and seven year old wood chips are then reviewed. Results of a field trial of wood chips are given. This trial monitored heat buildup in wood chips over two summer seasons.

A variety of geothermal analyses using a finite difference computer model are presented. The analyses includes provision for a time dependent heat generation function and changing functions for water content and thermal conductivity within the wood chips. The analyses include comparisons with observed behaviour at the test section, sensitivity analyses on critical parameters, and the results of predictions for typical field or design configurations. Construction aspects are briefly discussed and field wood chip configurations are illustrated.

INTRODUCTION

The construction of the Norman Wells Pipeline Project was completed by Interprovincial Pipe Line (NW) from Norman Wells, N.W.T. (kmp 0) to Zama, Alberta in the winter of 1984/85. This project consists of 868 km of 323 mm diameter pipeline transporting oil from Norman Wells. Permafrost occurs over a large proportion of the pipeline route but is discontinuous and varies in thickness from 50 m near Norman Wells to around 1 m near Zama. The pipeline is fully buried but the properties of Norman Wells crude allow the oil to be discharged at $-2^{\circ}C$ thereby restricting thermal input into the surrounding soil. A description of this project have been provided by Pick et al (1984), and Nixon et al (1984) have reviewed major aspects of pipeline design involving thaw settlement and frost heaving. This paper considers a major technical innovation in the use of wood chips used for insulation in order to maintain the integrity of permafrost slopes in the discontinuous permafrost zone.

BACKGROUND GEOLOGICAL SETTING AND SLOPE DESIGN PHILOSOPHY

From Norman Wells south to kmp 400, the pipeline parallels the east bank of the Mackenzie River, crossing many tributary creeks and rivers. Many of the slopes along this portion of the route are frozen. South of about kmp 400 the pipeline is located along the Great Slave Plain and, with the exception of the Mackenzie River crossing has been located so as to avoid major permafrost slopes. Because the pipeline crosses more than 150 slopes, the design process generalized the types of permafrost soils encountered into three major groups based on field description, laboratory testing and observed slope performance. The first major grouping was called ice-rich clay and encompasses frozen glaciolacustrine silts, clayey silt and silty clay soils, fine grained colluvium or slopewash-derived soils. Such soils typically have water contents greater than 25 to 30% within the zone of thermal disturbance. Thaw settlement tests on similar soils indicate that at water contents of less than 20 to 24% little, if any, thaw settlement will occur. All such fine-grained soils were considered ice-rich and there is no ice poor category adopted for design purposes. In some slopes, high water contents in the order of 50% or greater, visible ice contents greater than 30 to 50% and thick ice lenses, are encountered.

The next common category of frozen soil is an ice poor till. These tills are dense soils with water contents typically less than 10% to 15%. Thaw settlement tests indicate that tills with these low water contents do not settle significantly on thawing and, in fact, sometimes exhibit a minor tendency to swell. In some frozen slopes a minor component of dense frozen sands or silty sands can occasionally be encountered. For analysis purposes these well-draining soils are considered equivalent to ice poor till. An intermediate category of ice-rich till has been adopted for analysis purposes. This classification is used for till soils which have some visible ice and higher water (ice) contents.

While the pipeline, being more or less at ground temperature, does not influence permafrost slope stability, a fundamental component of geothermal disturbance results from right-of-way clearing and construction disturbance effects. Previous studies, for example McRoberts et al (1978), of thawing along cleared rights-of-way in the vicinity of the IPL line established that past terrain disturbance on cleared trails and roads initiates permafrost thawing. A review of available data indicated that complete removal of vegetation and severe damage to the organic surface cover could be expected to result in about 4 to 6 m of thaw over a 25 year period. Less thaw in the order of 1 to 4 m in 25 years, and in many instances no degradation at all, might be anticipated if construction disturbance was restricted to removal of trees alone. However, as this was viewed as being impractical it was recognized that pipeline construction would result in slope thawing.

Experience in the Mackenzie Valley, see McRoberts (1978), as well as a variety of unpublished studies of failed slopes has established that thawing of permafrost slopes causes failures. These studies supported by theoretical analyses of the type reported by McRoberts et al (1978) lead to the conclusion that slopes associated with the IPL project greater than 9^{o}, 13^{o} and 18^{o} in ice-rich clay, ice-rich till and ice poor till soils respectively would not be sufficiently stable during thawing or long term degradation. Two major mitigation concepts were evolved to develop a sufficiently high safety factor. In highly ice-rich slopes and/or for steeper inclinations it was specified that thaw had to be virtually prevented by being restricted to the natural active layer. In other slopes, depending upon angle, soil type and ice conditions thaw was permitted but at controlled rates.

In assessing potential mitigation measures, a variety of candidates were considered. Among these were a gravel/synthetic insulation sandwich, wood chips, wood chip/synthetic insulation sandwich, and a thermopile or cyroanchor/insulation mode. Wood chips were selected as the primary design mode for several reasons. Firstly, properties of wood chips provide a better overall geothermal solution. While the thermal conductivity is greater than artificial insulation (boards, or formed-in-place) the wood chips retain moisture and the high latent heat effect is important. Secondly wood chips can be placed directly on the slope during winter without high quality specification and expensive construction procedures. Because some thaw is inevitable, the rigidity of artificial insulation modes was considered to be a major disadvantage because of subsequent settlement. Finally, it was anticipated that some failure may occur either due to slope movements, or other effects and wood chips were viewed as being easy to rehabilitate. An environmental perspective, ultimately supported by regulatory agencies was that a renewable resource was being used (compared with gravel, often in short supply) and wood chips were the best choice.

There were, of course, certain disadvantages of wood chips. While the pipeline is situated in the boreal forest, tree harvesting would require development of wood lots off the right-of-way. Wood chips do not revegetate easily and in addition, there was the possibility of polluting leachates entering the surface water regime. Wood chips were also known to generate heat, due to micro-biological action, and this effect as well as possible deterioration of thermal properties with time required study. The wood chips exert only a minor surcharge on the sloping soil and little benefit in improving effective stresses at the thaw line could be expected. Finally there was some concern that the wood chips might not be stable themselves and could be eroded or become buoyant during a heavy rainfall.

While it is generally held that wood chips might serve as an insulative material, there is a general lack of well documented precedence. Certainly sawdust and shavings has been used in Canda for many generations as an insulative material in houses, and prior to mechanical refrigeration to store ice during summer months. Wood chips and sawdust have also been used as light weight road fills in muskeg terrain. It was known that wood chips have been used in the Mackenzie Delta as expedient pads for transportation of drill rigs and the Canadian National Railways have used them south of Churchill, Manitoba in conjunction with cryo-anchors, see Anon (1983), to reduce thaw in railroad embankments.

Wood chips and tree bark have been used in the past in road construction in Sweden to reduce seasonal frost actions. Gandahl (1970) notes that bark from pine and fir trees have been tested in Sweden for ten years, and proved to be a good road subgrade material. Frost penetration resistance is considered good because of the capacity to store water, in addition to a reasonable bearing capacity, and good thermal insulating properties. The total known length of roads constructed with bark layers in north and central Sweden is in the range of 60 km. The bark layer is placed directly on the moist subgrade to a thickness of 30-60 cm, and a gravel base is placed over the bark to provide a trafficable layer.

Wood chips are a common product of the pulp and paper industry in North America and some experience is available concerning the behaviour of large piles of wood chips and sawdust. Wood chips piles can generate heat due to both respiration of still living wood cells, but primarily due to the fungal action of a variety of micro-organisms, primarily fungi, see Hajny (1966). The action of such fungi is to reduce the amount of wood substance. Brown rots primarily associated with the types of soft woods available (pine, spruce) preferentially utilize cellulose leaving the lignen untouched, see Shields (1977), and therefore leave the essential structure of the chip intact. This bacterial action gives rise to heat generation which promotes further fungoidal action. Temperatures up to 40-60°C an be found in large wood chip piles in the order of 20-25 m high. Experience in the forest industry is that chip deterioration is sharply reduced in smaller piles where the surface area to volume ratio is greater. Chemicals such as borax and sodium carbonate have been used by the forest industry to reduce wood loss and heat buildup, Shields (1977). However, such applications raised environmental issues and in the long term would likely require re-application of chemicals.

In summary then, as the design of the Norman Wells pipeline evolved, it became clear that measures were required to either essentially eliminate or retard thaw in permafrost slopes. Wood chips offered several cost advantages and were considered the best solution from several technical perspectives. However, it was clear that a variety of studies were required to define the appropriate thermal properties of chips, to account for the possible influence of heat generation, and to allow for the likely reduction of wood substance with time.

GEOTHERMAL ASPECTS OF CLEARED RIGHTS-OF-WAY

Most of the permafrost slopes along IPL line are located in a distinct climatic zone extending from Norman Wells south to near kmp 400. The mean annual air temperature in this region is around -6.7°C. South of this region warmer temperature characteristic of the Great Slave Plain region are in the order of -3.9°C. Investigations of thaw degradation along older previously cleared rights-of-way discussed earlier, as well as geothermal analysis, established a base case for thermal degradation. Detailed interpretation of observed thaw data indicated that the wide of a disturbed right-of-way also influenced thaw depth. For example, it was found that doubling the cleared with from 10 to 20 m could result in a doubling of thaw depth. While such an effect is in accordance with theory, it was difficult to quantify because of a lack of site specific permafrost temperature data. The data did, however, support the concept of the narrowest possible cleared width in order to assist in minimizing deepening of the permafrost table.

Detailed geothermal studies using the Hardy Associates simulator, see Nixon (1983), were used to match observed thaw with computer simulations using realistic air temperatures, ground temperatures and ground thermal properties. That is, a computer model of realistic worst case thermal degradation of permafrost was set up and the best fit properties so obtained used in subsequent analysis of the mitigative techniques.

TEST SITES

Interprovincial Pipe Line (NW) Ltd. established a wood chip test site near Grande Prairie, in northern Alberta, in July 1983. Two 10 x 10 m wood chip plots, 1.2 m in thickness were constructed, complete with diversion berms and temperature monitoring, on a 30% (16.7°) slope. The lower plot also included a plastic covering. The layout is given on Figure 1. Wood chips were placed using a rubber-tired loader, and finished using hand labour. Readings of temperature instrumentation were taken after installation, and several times in the following year. The site was discontinued at the end of July 1984.

A second site was visited near Norman Wells, N.W.T., to obtain samples and a visual appreciation of the properties of a seven year old berm of wood chips. Thermal properties and the physical deterioration of this wood chip plot are discussed later.

HEAT GENERATION

Different aspects of the geothermal design for the Norman Wells Pipeline were handled by the Hardy Associates (HAL) one and two dimensional thermal simulators. For simulations involving wood chips on sloping terrain, the HAL one-dimensional thermal simulator was modified to account for internal heat generation in the surface wood chip layer. Normally, the one-dimensional equation heat transfer is described by the classical diffusion equation as follows:

$$C_o \frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x} \left(k \frac{\partial \theta}{\partial x}\right) + Q_g(\theta, t) \qquad (1)$$

where: C_o = the volumetric heat capacity ($J/m^{3\,o}C$)

k = temperature dependent thermal conductivity (W/m^oC)

θ = temperature (^oC)

t = time

x = depth

The additional term on the right hand side of the equation, $Q_g(\theta,t)$, is the rate of heat generation per unit volume of the soil or wood chips mass.

It is known from data published from the forest industry that large piles of wood chips or sawdust will experience rises in temperature with time due primarily to fungal breakdown of the wood chips in the long term. The rate at which temperatures can dissipate from this heat generation process is very dependent on scale effects. Thin layers of wood chips will tend to equalize rapidly with the surrounding environment or ambient temperature conditions, whereas large piles of wood chips will tend to self-insulate and allow the maintenance of excess temperatures in the centre of the wood chip mass. The possibility of excess temperatures within the wood chip pile was acknowledged during the design process, and the above equation was solved using the modified version of the HAL one-dimensional simulator to account for such effects.

Various literature sources including Shields (1977), Springer and Zoch (1970), Saucier and Miller (1961), and others indicate that temperature increases can be as much as 3-3.2^{o}C/day, possibly attaining temperatures of up to 43 to 46^{o}C after some time. Apparently, after these temperature levels are achieved, the temperature returns gradually to ambient level after some months.

The initial heat generation rate during a rapid rise in temperature can be estimated based on the assumption that no temperature dissipation from the wood chips occurs to the outside environment in the short term, and therefore equation (1) can be written as:

$$Q_g\ (\theta, t) = C_o \frac{\partial \theta}{\partial t} \qquad (2)$$

This equation is only valid in the very short term, when the rate of heat generation is initially high, and the rate of dissipation to the surrounding environment is small when compared to internal rate of heat generation.

Initial heat generation rates based on the published literature and our observations at the Grande Prairie test site and the field slope instrumented sites vary between 30-68 W/m^3 (0.62-1.4 $cal/cm^3/day$). Material from the Pulp and Paper Research Institute of Canada (see Hatton (1983), was combined with a knowledge of the total heat of combustion that would occur if all wood material was lost. The total quantity of heat which can be liberated by a given volume of wood chips can be estimated based on the total heat of combustion, which is often cited as 10.9 MJ/kg (2610 cal/gm) of dry wood chips, or about 10.9 x 150 = 1638 MJ/m^3 (392 cal/cm^3) for a wood chips layer having a dry density of 150 kg/m^3. That is, the total amount of heat liberated in the long term by any unit volume of wood chips has an upper limit of this amount. The question remained as to how this initial heat generation rate reduces with time, and with each season, to result in a total heat generation not greater than the figure outlined above.

Initial thermal simulations carried out for design purposes assumed an exponential reduction in the heat generation with time, as given by the following equation:

$$Q_g = Q_o \exp(-\alpha t) \qquad (3)$$

However, this relationship is further complicated by the seasonal and temperature dependence of the heat generation function. From a review of the published literature and conversations with Forintek Canada Corporation, it appears that vigorous fungal decay in the wood chips does not commence until the temperature exceeds somewhere in the range of 10°C. In addition, at some temperature in excess of 45 to 60°C, this activity will be inhibited because of the excessive temperature level. Therefore, for the purposes of design simulations, the heat generation function was assumed to increase linearly from zero to its full design level between a temperature of between 10 and 15°C, and remains at this level until a temperature of 45°C was exceeded. Above this level, the rate of heat generation was assumed to decrease linearly to zero between a temperature of 45 and 60°C.

Observations of the older wood chips at Norman Wells indicated that most or all of the fungal decay within the wood chips has been completed within a period of seven years. Consequently, the rate of reduction in the heat generation function as expressed by equation (3) was adjusted accordingly in such a way as to dissipate most of the heat generation within any element of the wood chip layer within the first seven years. Various heat generation functions have been applied within the HAL geothermal program to modelling the wood chips at different locations, and the precise function adopted will be related to the climate and the actual makeup of the wood chips used. It should be noted, however, that whatever heat generation function is adopted, the total amount of heat generated within any volume of wood chips cannot exceed the total amount outlined above.

From observations at the Grande Prairie test site and the older wood chips at the Norman Wells site, it has been observed that the water content and therefore other relevant thermal properties of freshly harvested wood chips increase from 60-80% by dry weight to in the range of 200% by dry weight after several years. Therefore, the one-dimensional model also contains temperature dependent water content, thermal conductivity, and heat capacity functions that vary expontentially with time.

Figure 2 shows a comparison between observed temperatures at the Grande Prairie test site with time, and those simulated using an initial heat generation rate of Q_o = 68 W/m^3 (1.4 cal/cm^3.day), and a rate of reduction of the heat generation function as given by $\alpha = 0.0163$. The simulation appears to agree reasonably well with the average of two observations from two different thermistor strings embedded within the wood chip pile. The second year observations at the Grande Prairie test facility indicate that heat generation occurs in a similar fashion in the second year, at a somewhat reduced rate. These observations are generally consistent with the model for heat generation in wood chips as it is currently formulated.

When these heat generation functions are introduced into the model and applied to the design of insulated slopes along the Norman Wells pipeline R.O.W., the effects of heat generation can be seen as shown on Figure 3. The introduction of an appropriate heat generation function causes a small increase in long term depth of thaw, and the use of 1.2 m of wood chips is estimated to limit the thaw into original soil to about 1.5 m after a 25 year period.

The overall effect of different thicknesses of wood chips on retarding the long term rate of thaw in cleared pipeline ROW is shown on Figure 4. In addition, this figure also shows the effect of removal of a surface layer of 0.15 m of peat. Generally, the depth of thaw in the long term is increased when the thickness of wood chips is reduced. It should also be noted that as the thickness of the wood chips is increased in the range of a metre, the effect at surface removal of peat becomes fairly minimal.

THERMAL PROPERTIES

The primary thermal properties of interest are the volumetric heat capacity and thermal conductivity of the wood chips in both the frozen and thawed state. The latent heat of the chips is also of significance in geothermal analysis but this is calculated from a knowledge of the representative water content and dry density.

Two major sources of chips were tested for thermal properties. The first source involved fresh chips and a second series of samples was obtained from the older chips from Norman Wells, N.W.T. This pile was made from black spruce logs chipped during the winter of 1976/77 and was approximately 1.2 m deep. Samples of the seven year old chip material were studied by the Pulp and Paper Research Institute of Canada (see Hatton, 1983) and concluded that degradation resulting in extensive loss of material had occurred but that because all easily accessible cellulose had been removed the future rate of cellulose metabolism would be low. In addition, Hatton (1983) concluded that the degradation observed was strictly due to fungal action rather than heat degradation. Therefore testing of these older chips would likely give a good measure of long term properties.

A number of different tests were carried out on both fresh and aged wood chips. These include freeze-thaw cycling tests, heat capacity testing, thermal conductivity testing of both fresh and older wood chips. During the freeze-thaw cycling test, samples of fresh pine wood chips were placed in a large lucite cell, and subjected to a total of 16 cycles of wetting, drainage, freezing, and thawing. A summary of the test results for one sample is shown on Figure 5. It is seen that the dry density started at approximately 135 kg/m^3 and increased to about 160 kg/m^3. This is a similar dry density to that observed in the Norman Wells seven year old wood chips under natural field conditions. During the same period, the water content of this particular sample increased from 120% to about 190% by dry weight. The corresponding degree of saturation increased from about 18% to 34%. The properties at the conclusion of these tests were similar in many respects to the properties obtained from the field examination of the Norman Wells test embankment of wood chips, and therefore the thermal properties of these samples could be expected to be similar during this artifical simulation of 16 cycles of freezing, thawing, wetting and drying. These relationships in general terms provided an impression of how the physical properties of the wood chips could be expected to change with time. The bio-degradation of the wood chips can not be simulated by this accelerated aging process.

A total of 21 thermal conductivity tests were carried out on samples of wood chips both frozen and unfrozen, fresh and aged. Three of these tests were carried out at the completion of the three freeze-thaw cycling tests mentioned above. The thermal conductivity of the frozen wood chips varied generally between 0.1 and 0.46 $W/m^{o}C$, depending heavily on the water content of the material. The unfrozen thermal conductivity of the wood chips generally lay between 0.08 and 0.23 W/m°C. At a water content of 210% by dry weight, the values used for design of the permafrost protection for the slopes was k = 0.21 W/m°C for unfrozen wood chips and k = 0.36 W/m°C for frozen wood chips. These values were measured using a thermal heating probe, of the type described in ASTM D2326. This probe was about 1.2 cm in diameter and about 15 cm long, and was inserted in a small hole made in the wood chip sample. Figures 6 and 7 provide the relationships between unfrozen thermal conductivity and water content or degree of saturation of the wood chips. The strongest correlation emerges between the conductivity and the water content of the sample, and the dashed line on Figure 7 provides the proposed relationship between conductivity and water content.

It is interesting to note that the properties of the aged wood chips seemed to tend towards the published values for peat conductivity at the same water content of 210% by dry weight, see Table 1.

TABLE 1

DETERIORATION IN THERMAL PROPERTIES WITH TIME

Time (years)		Conductivity	
		Unfrozen k_u (W/m°C)	Frozen k_f (W/m°C)
0	(Fresh)	0.10 or less	0.10 or less
7	(Norman Wells)	0.21	0.36
	Peat*	0.24	0.4

* Based on Kersten's published data for peats at a water content of 210% and a similar dry density to the 7-year old Norman Wells wood chips.

Two calorimeter tests were carried out to confirm the volumetric heat capacity of moist wood chips. A large highly insulated calorimeter was half filled with water at a known temperature. A sample of moist wood chips was placed in a vacuum flask and totally de-aired to ensure that the sample would immerse when placed in the calorimeter. The sample of wood chips was thermally conditioned, then placed in the calorimeter. The change in temperature of the contents provided the volumetric heat capacity. These values agreed well with a calculated heat capacity based on the heat capacity of the constituents. Typically, the volumetric heat capacity of moist wood chips was in the range of 0.2 to 0.46 times that of water, depending upon the amount of aging, the degree of saturation and the water content of the samples.

DESIGN CONFIGURATION AND CONSTRUCTION COMMENTS

The requirement for an insulation solution for thawing slopes was established by slope stability analysis following the approach discussed by McRoberts (1978) and McRoberts et al (1978). These analyses found that the influence of thermal disturbance on slopes less than 9^{o}, 13^{o} and 18^{o} inclination in ice-rich clay, ice-rich till and ice poor till slopes, respectively was acceptable. As previously discussed, wood chips were found to be the most appropriate mitigative solution for a buried pipeline. A range of design studies were then undertaken to define the necessary wood chip thickness to obtain suitably stable slopes.

In highly ice-rich slopes, thaw depth was limited to the naturally occurring active layer. In practical terms, this resulted in the specification of a 1.5 m thick layer of wood chips with a long term thaw depth of 1.1 m into the original soil profile (see Figure 3).

Depending on overall slope inclinations, soil type and slope angle, long term thaw was permitted. Under these circumstances the target for geotechnical analyses involving slope stability was to obtain a factor of safety in the range of 1.25 to 1.5 for static loading conditions and 1.0 under the design seismic event. These analyses took into account the following effects:

- Permafrost thaw rates and depth established by geothermal analysis
- The changing influence of effective stress strength components (c', ø') as the effective stress on the thaw front changed with thaw depth
- The varying influence of pore pressure effects as thaw proceeded deeper, and at the same time the rate of thaw reduced with time
- The varying dimensions of the thawed zone, as thaw proceeded deeper into the slope
- The influence of the design probable seismic event which was considered to be equivalent to a near-field magnitude 5 event.

These analyses resulted in the specification of wood chip thickness ranging from a minimum of 0.3 to 1.4 m in thickness.

Pre-construction inspection of all slopes, coupled with field drilling of steeper and more sensitive slopes established the appropriate design mode for all slopes. In addition, during construction a senior geotechnical engineer inspected all slopes during grading and ditch excavation was completed and made a final judgement regarding the wood chip thickness and necessary coverage along the right-of-way.

The method of harvesting and placing wood chips was left to the contractor, who elected to chip at the harvest site and truck the chips to the required location. Wood chips were then dumped at the top of slope and spread downslope by a light bulldozer. Figure 8 is an example of a typical placement operation. Pipeline construction specifications call for the placement of erosion control measures on slopes. Such provisions were judged to be necessary in most slopes and water diversion berms were placed at appropriate intervals on the slope. Wood chips were then placed over the diversion berms.

It was recognized that field monitoring of the geothermal performance of wood chips was an integral part of the design in order to ensure that design assumptions were realized. Representative slopes have been instrumented with closely spaced thermistor devices in both the wood chips and underlying permafrost. Monitoring during the summer of 1984 indicated that heat generation within the wood chips did occur. Generally speaking, field performance has matched predictions, although there has been a tendency for greater thaw than expected in some of the ice poor permafrost slopes. This, however, is not viewed as serious as such slopes are better able to withstand the geotechnical consequences of thawing.

The summer of 1984 saw periods of intense rainfall in the Norman Wells area in the vicinity of slopes constructed during the first 1983/84 winter season. The wood chips withstood these rains and have performed satisfactorily.

CLOSURE

Wood chips have been successfully applied to the thermal protection of slopes in permafrost areas. Wood chips are a renewable resource, are locally available and are relatively easy to harvest, process, transport and place.

The HAL one-dimensional thermal simulator has been modified to handle both temperature and time-dependent heat generation effects within the upper layer of wood chips. Thermal properties have been measured in the laboratory and when input to a thermal model, the procedure has predicted many of the important features observed in the field. The model has also been used to predict the expected long term thermal performance of wood chip layers when used for permafrost slope protection.

It is important to note that several more years of observations will be required before the heat generation and long term thermal aspects of wood chip layers in the sub-arctic will be more fully understood based on data from this project. Predictions and simulation procedures described in this paper represent early, but reasonable estimates of the performance of wood chip layers in the field.

Modification of simulation procedures and an improvement in the understanding of long term performance can be expected in the future, as field data from different instrumented sites are accumulated.

ACKNOWLEDGEMENT

The authors are grateful to Mr. Bill Pearce of Interprovincial Pipe Line (NW) Ltd. for permission to publish this material. In addition, input from many of their colleagues at Hardy Associates (1978) Ltd., Interprovincial Pipe Line and their consultants is sincerely appreciated.

REFERENCES

Anon 1983. Engineering News. Canadian Consulting Engineer Vol. 25, No. 2.

Forintek Canada Corp., 1983. Biological breakdown of wood chips. Report to Hardy Associates, dated June 9, 1983.

Gandahl, R., 1970. Byggande med bark i vag. Statens Vaginstitut, rapport 110, Stockholm. (Also personal communications on the use of bark as a road building material in Sweden.)

Hajny, G.J., 1966. Outside storage of pulpwood chips: a review and bibliogrpahy. Tappi Vol. 49, No. 10.

Hardy Associates (1978) Ltd., 1983. Geotechnical aspects of wood chip insulation design for permafrost slope protection. Report to Interprovincial Pipe Line (NW) Ltd., March 1983.

Hatton, D., 1983. Report on analysis of wood chips prepared by Pulp and Paper Research Institute of Canada to Hardy Associates Environmental Division, dated February 16, 1983.

McRoberts, E.C., E. Fletcher and J.F. Nixon, 1978. Thaw consolidation effects in degrading permafrost. Third Intl. Conf. Permafrost, Vol. 1, pp 694-699.

McRoberts, E.C., 1978. Geotechnical engineering for cold regions. McGraw Hill Book Company. Editors, D. Andersland and D. Anderson.

Nixon, J.F., 1983. Practical applications of a versatile geothermal simulator. Proc. Am. Soc. Mech. Eng., Journal of Energy Resources Technology, Vol. 105, No. 4, pp 442-447. Dec.

Nixon, J., J. Stuchly and A. Pick, 1983. Design of Norman Wells pipeline for frost heave and thaw settlement. Am. Soc. Mech. Engineers, Proc. 3rd Intl. Offshore Mechs. and Arctic Engineering Symposium, New Orleans, La. Feb. 12-16.

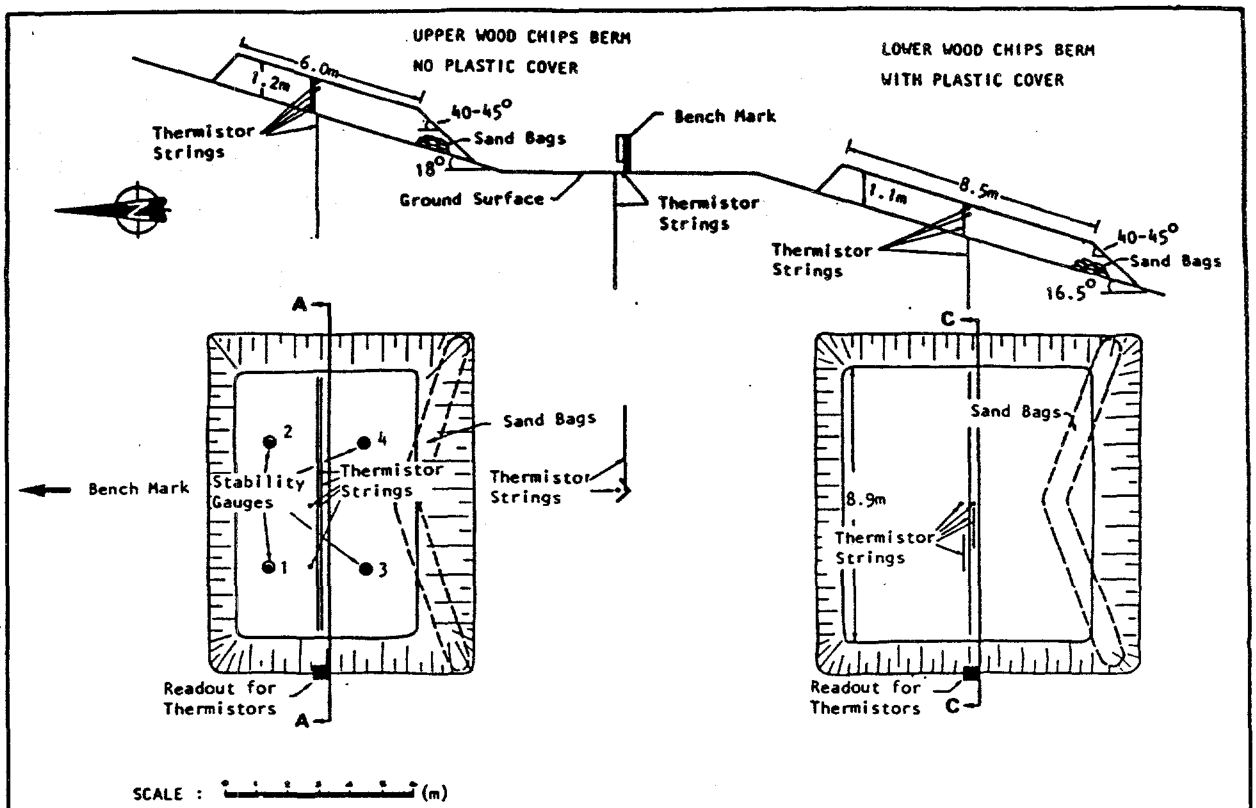
Pick, A., H. Sangster and J. Smith, 1984. Norman Wells Pipeline Project. Proc. ASCE/CSCE 3rd Intl. Specialty Conf. on Cold Regions Engineering. April 4-6, Edmonton, pp 11-18.

Saucier, J. and R. Miller, 1961. Deterioration of southern pine chips. Presented at Annual Meeting of Forest Products Research, Louisville, Ky. Session 13. Also in Forest Products Journal, pp 371-372.

Springer, E. and L. Zoch, 1970. A simulator of an outside chip pile. Journal of the Technical Assoc. of the Pulp and Paper Industry. Vol. 53, No. 1, Jan. pp 116-117.

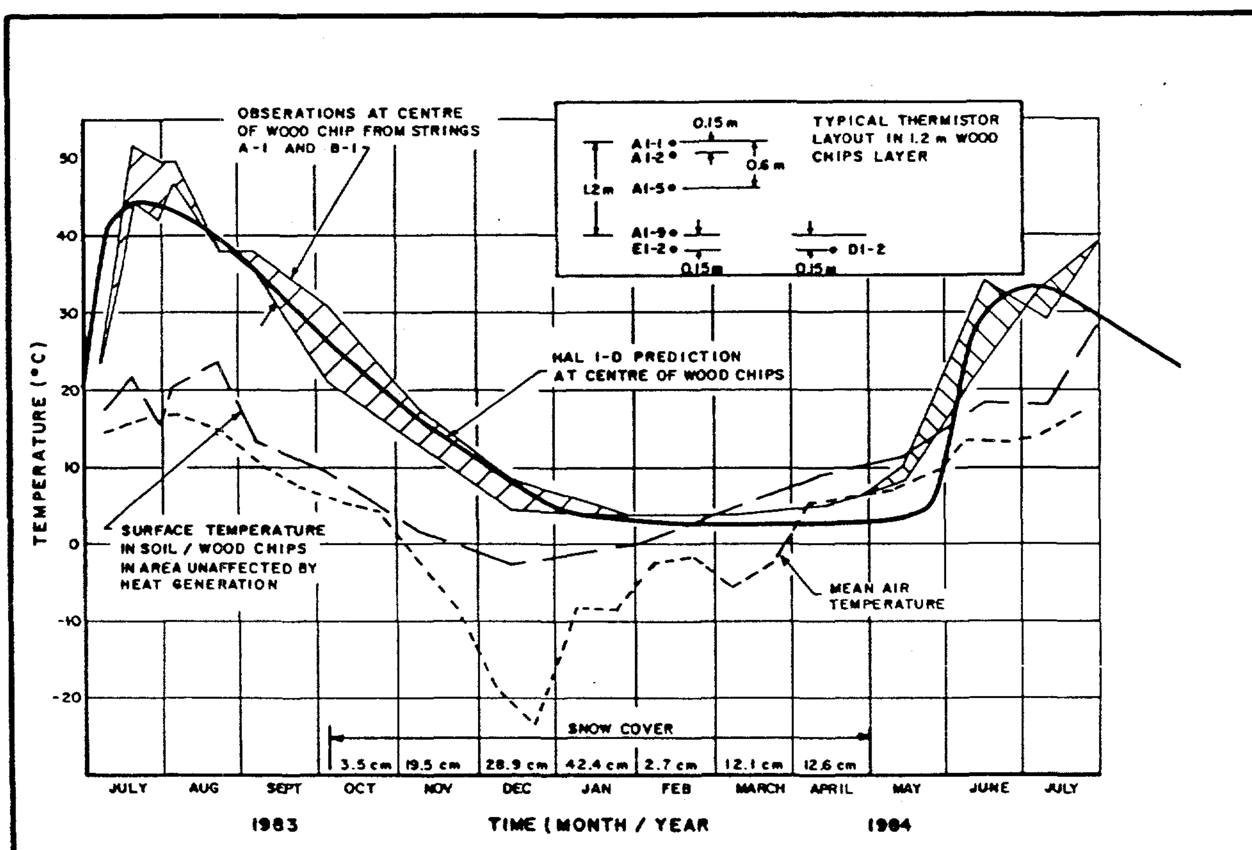
Shields, J.K., 1977. Store chips this way and reduce your losses. Eastern Forest Products Laboratory. Environment Canada Forestry Service Bulletin LD7E. 4 pages.

11/12



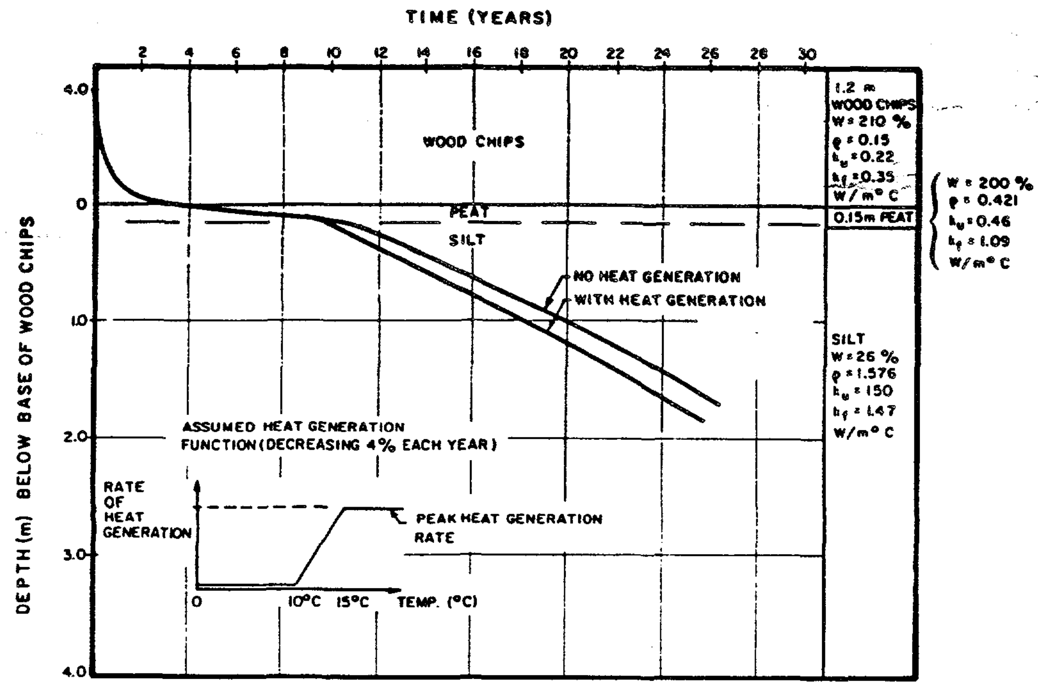
WOOD CHIPS TEST SECTION - PROFILE AND PLAN
GRANDE PRAIRIE, ALBERTA

Figure 1



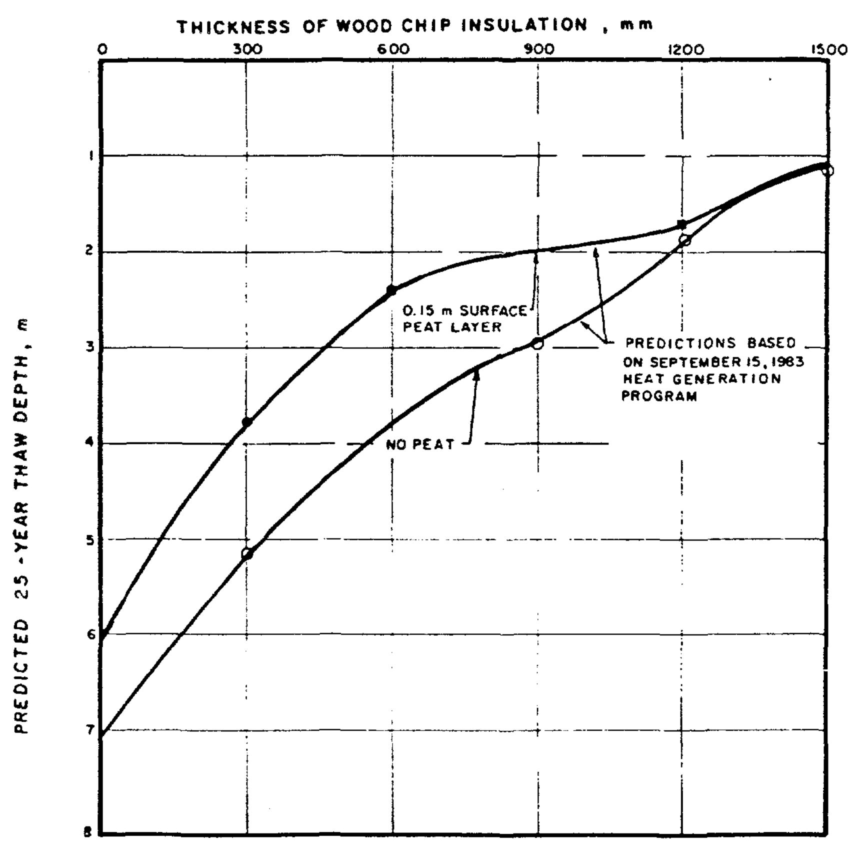
PREDICTED AND OBSERVED TEMPERATURE
AT GRANDE PRAIRE
WOOD CHIP SITE WITH TIME

FIGURE 2



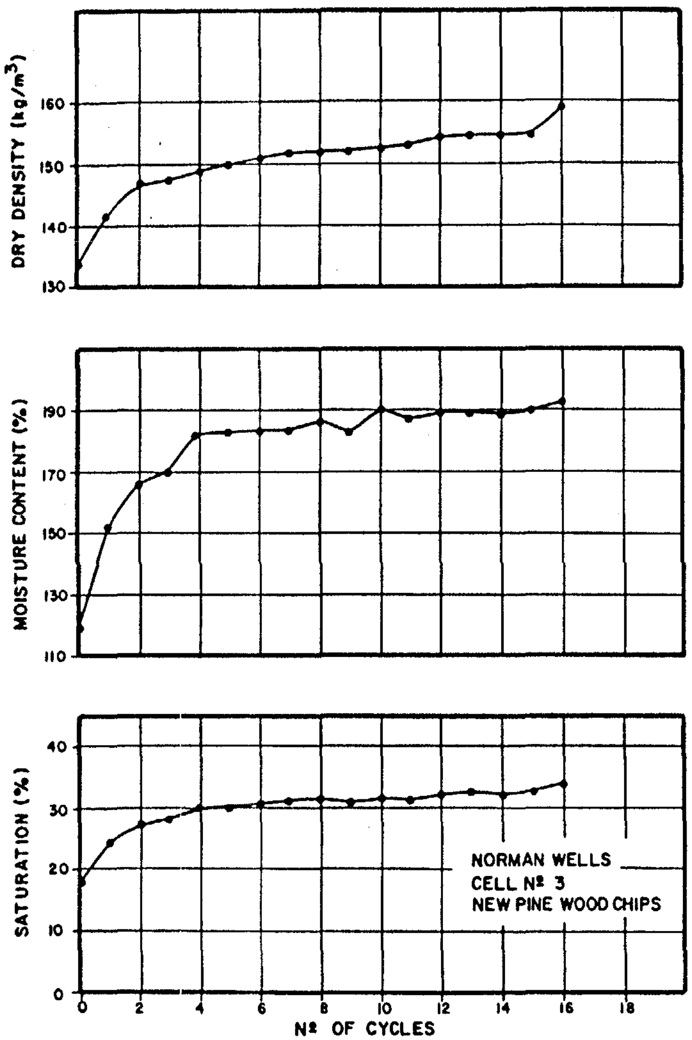
THAW DEPTH BENEATH 1.2 m WOOD CHIPS LAYER, WITH AND WITHOUT HEAT GENERATION

FIGURE 3



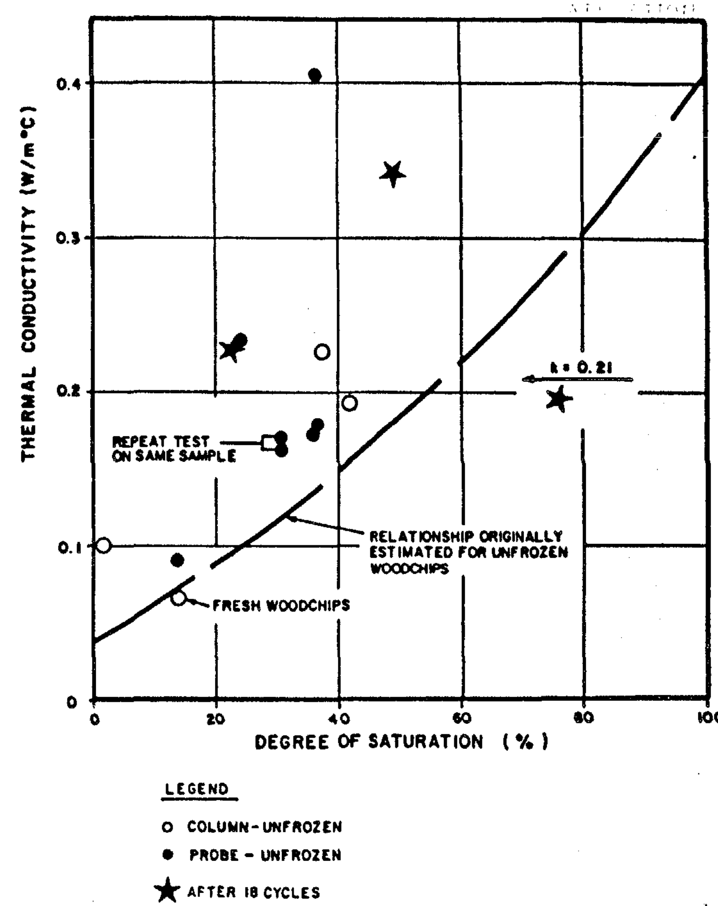
HEAT GENERATION AND CONSTRUCTION EFFECTS ON PREDICTED THAW DEPTHS

FIGURE 4



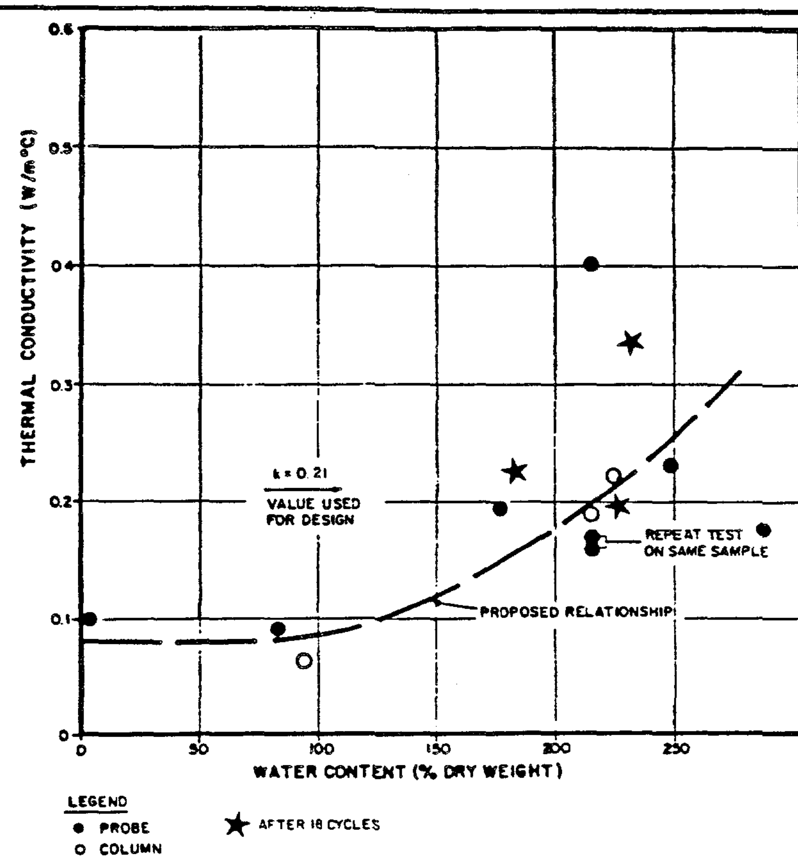
CHANGES IN PHYSICAL PROPERTIES
WITH SOAKING AND FREEZE-THAW CYCLING

FIGURE 5



UNFROZEN THERMAL CONDUCTIVITY
AND SATURATION

FIGURE 6



UNFROZEN THERMAL
CONDUCTIVITY OF WOODCHIPS

FIGURE 7

WOOD CHIPS PLACEMENT ON

NORMAN WELLS PIPELINE R.O.W.

Figure 8

THE NORMAN WELLS PIPELINE PROJECT

INTRODUCTION

The Norman Wells pipeline is 538 miles (868 km) long, 12" (324 mm) diameter and carries approximately 25,000 b/d of API crude from the Norman Wells oilfield in the Northwest Territories to Zama in Northwest Alberta where it enters existing pipeline delivery systems. It is owned and operated by Interprovincial Pipeline (NW) Ltd. (Fig. 1).

The line was put into service April 17, 1985 after almost six years of planning, public hearings, design and construction. As the first crude line in Canada's north it was subjected to considerable political and regulatory scrutiny, which resulted in stringent environmental and socio-economic conditions added to the significant design restraints for permafrost areas and a two year mainline construction timetable.

The project was considered by many groups to be a pilot model for future arctic pipelines in Canada, and certainly has provided industry with experience which previously had been limited to Alaska.

Project Setting

Climate. The pipeline is built in a region which is classified as sub-Arctic. The area is characterized by long, cold winters and short warm summers.

January is the coldest month with temperatures averaging between -25 and -30°C; lows of -40°C are common. Snowfall accumulation varies, averaging between 1 and 1.4 metres. During the winter the minimum daylight hours vary from 3 hours at Norman Wells to 6 hours at Zama.

The summer is characterized by hot dry long days with only two or three hours of full darkness during early July.

Terrain. For the first 526 km the pipeline generally follows the Mackenzie River. The terrain is rolling with numerous valleys and high flat terraces. Well drained areas are covered in forests of pine, white spruce, poplar and aspen with poorly drained areas covered in black spruce and tamarack. The route crosses the Mackenzie near Fort Simpson.

South of the crossing the route is generally flat and poorly drained. The area is dominated by open coniferous forests of dwarfed black spruce and tamaracks with intermittent significant areas of bog and fens.

Permafrost occurs over a very large proportion of the pipeline route. The permafrost is dicontinuous, varying in depth from 50 m near Norman Wells to scattered patches 1 m thick near Zama. The active layer varies from 1 m or less near Norman Wells to up to 3 m near Zama.

Drainage. Because much of the route follows the Mackenzie River the pipeline crosses numerous drainages. There are approximately 160 identifiable crossings ranging from intermittent small streams to a major crossing of the Mackenzie River. There are 11 streams crossed that are classified as navigable waters under the Navigable Waters Protection Act. The Mackenzie River and the Great Bear River are considered as major crossings.

REGULATORY PROCESS

In Canada, oil pipelines crossing a Provinical or International boundary are subject to the jurisdication of the National Energy Board. The Company applied early in 1980 for authorization to build and operate the line and the NEB held extensive public hearings in a judicial format prior to issuing its "Reasons for Decision."

The land was owned by the "Crown" represented by the Government of the Northwest Territories, the Federal Department of Indian Affairs and Northern Development and the Government of Alberta. Following an application for a right-of-way, the Federal Environmental and Review Office (FEARO) initiated its own public hearings which resulted in a set of socio-economic and environmental recommendations for consideration by the various government agencies.

The applications and hearings resulted in four major authorizations and agreements:

> The NEB Certificate of Public Convenience and Necessity authorizing the pipeline construction subject to completion of engineering, socio-economic and environmental studies with considerable review by intervenors.
>
> The Environmental Agreement with both Federal and Territorial governments requiring the production approval and implementation of a series of "Action Plans."
>
> The Socio-Economic Agreement with both Federal and Territorial governments requiring the production approval and implementation of a series of "Action Plans."
>
> The Pipeline Agreement with the Government of Alberta giving particular emphasis to special environmental requirements.

In addition to these major agreements, IPL sought and received approximately 200 licences, permits, authorizations, exemptions, agreements, amendments and consents provided for under various federal, territorial and provincial statutory requirements.

Inspection staff of the NEB were on site to ensure that the construction follows the requirements of the Regulations and the Certificate. Inspectors representing the Department of Indian and Northern Affairs, the Government of the Northwest Territories, the Department of Fisheries and Oceans and the Province of Alberta were on site to monitor for compliance with the various permits, licences and authorizations.

PROJECT MANAGEMENT

Project Organization

The owner/operator of the Norman Wells Pipeline is Interprovincial Pipe Line (NW) Ltd., (IPL). IPL managed and directed all phases of project construction and operation. The Company retained all major policy authority, Governmental and Regulatory interface, Socio-economic management, and Northern Relations management. It selected specialized consultants in two general areas.

Project management was divided into mission oriented functional groupings as follows:

Technical Services Management. The principal roles of technical services management (TSM) was to execute the planning and design functions for the project. Consultants were selected to perform the detailed pipeline design, including stress analysis, geotechnical studies and design, environmental studies and design, pump station design, cathodic protection system design, communication and SCADA system design.

Construction Services Management. To facilitate procurement of material and construction contractors services, cost control, management and inspection during construction. CSM services were provided by a joint venture company providing procurement, project cost accounting and field engineering services. A field inspection staff of approximately 75 inspectors was organized to provide quality control of three spreads during construction. IPL contracted two independent radiographic-inspection firms to provide 100 percent radiographic examination of welding. In addition, an independent audit of weld quality and radiographic interpretation was conducted by a separate group. The line was internally surveyed to identify dents, buckles and ovality.

Project Schedule

Construction of the Norman Wells Pipeline was planned to take place over the course of three years, with mainline pipeline being done during two winter periods. It was planned to be ready to begin service in the second quarter of 1985.

Because of the nature of the terrain, active travel on the land is restricted to the winter months. In the Northwest Territories, travel on the land, without all weather roads, is prohibited after early April.

For planning and contractual purposes, the pipeline route was divided into six construction spreads. Based on land-use restrictions, construction schedules were developed calling for construction of pipeline Spreads 1, 4 and 6 during 1984 and Spreads 2, 3 and 5 in 1985.

Pre-construction commenced in January 1983 with right-of-way clearing on Spreads 1, 4, 5 and 6. Development of numerous construction facility sites such as stockpiles, barge landings, camp sites, borrow sites, was also started during the winter of 1983. To meet land-use constraints, development of sites generally requires that clearing of sites and stockpiling of gravel occur during the winter of the year prior to use.

Pump station and maintenance facilities were built during the summer of 1984.

Transportation

The planning and execution of a Northern pipeline project requires considerable logistical planning. This is particularly true of the Norman Wells Pipeline where transportation realities imposed constraints on lead time for design and procurement if the 1985 start-up schedule was to be met. (Fig. 1).

Highway. The Alberta highway system leading to the Mackenzie Highway provides year round all-weather access to the pipeline route as far north as Fort Simpson. A limitation is the crossing of the Liard River which is serviced by ferry in summer and ice bridge in winter.

Highway travel to the pipeline route north of Fort Simpson is limited to travel on a winter road which is usually open from mid-January to the first of April. Travel on the Mackenzie Highway north of Fort Simpson during the summer is prohibited by the absence of bridges on the Mackenzie River, Willowlake River, and a number of minor streams.

Railroad. Railroad access is available as far north as Hay River via the Northern Alberta Railway and this intersects southern highway access to the pipeline route. The railroad terminates at the barge docks in Hay River.

Barge. Barge transportation to the Northern pipeline route is available from Hay River, NWT. The normal barging season is from June 15 to the end of October. Stockpile sites were constructed adjacent to the river north of Fort Simpson.

Air Service. Air service is available in proximity of the pipeline by scheduled air carriers to Rainbow Lake, Alberta, Ft. Simpson and Norman Wells, Northwest Territories. In addition, community strips are available at Fort Norman and Wrigley in the Northwest Territories. All phases of pipeline planning and construction operations have been regularly supported by helicopter and fixed wing charter operators in Norman Wells, Fort Simpson, and High Level, Alberta.

SYSTEM DESIGN

Background

For the first fully buried oil pipeline in permafrost terrain, the design concepts were developed to limit thermal inputs to the environment and to increase the strength of the pipe to provide for additional loadings caused by thaw settlement and frost heave. Loadings considered in the design included pressure, temperature differential, thaw settlement, frost heave and seismic loads.

Because of the properties of Norman Wells crude the oil is capable of being pumped easily at temperatures of -2°C. Discharging oil at this temperature at Norman Wells allows oil temperatures to be controlled to ground temperature, restricting thermal input to the environment.

Geotechnical Inputs to Pipeline Design

Location of the pipeline in an area of discontinuous and intermittent permafrost presents some extroardinary problems to be considered in desgin including thaw settlement, frost heave and slope stabililty.

The permfrost distribution is summarized in Table 1 including the number of discontinuities estimated by geophysical survey.

Table 1
Norman Wells Pipeline Project
Permafrost Distribution Along Route

Section of Line	% Frozen	No. of Discontinuities
0 - 150 km	84	259
150 - 270	66	513
270 - 380	69	342
380 - 528	32	592
528 - 696	16	532
696 - 868	35	1708

Many of the slopes over the length of the pipeline route had been identified as sensitive on the basis of soil type, permafrost content and steepness. Over 150 slopes were examined and subjected to specific design treatment.

Thaw Settlement. Although care has been taken to minimize land disturbance, clearing and construction activities will cause the permafrost to degrade.

During studies for this project it was determined that for the rights-of-way which had been cleared and subsequently undisturbed the depth of thaw will be in the range of 1 to 4 m at 25 years, whereas subsequent grading or similar disturbance will increase the depth of thaw to 4.5 to 6.5 m at 25 years. This disturbance of permafrost in areas of discontinous or intermittent permafrost results in differential settlement across the transition. On the basis of an extensive examination of borehole data and thaw settlement test sites, a design differential thaw settlement of up to 0.8 m was established for mineral soils and 1.2 m for organic soil deposits. Loading at a thaw settlement transition involves downward loading within the thaw settling ground and restrain to pipe movement in the thaw stable ground.

Differential Thaw Settlement outline is shown on Figure 2.

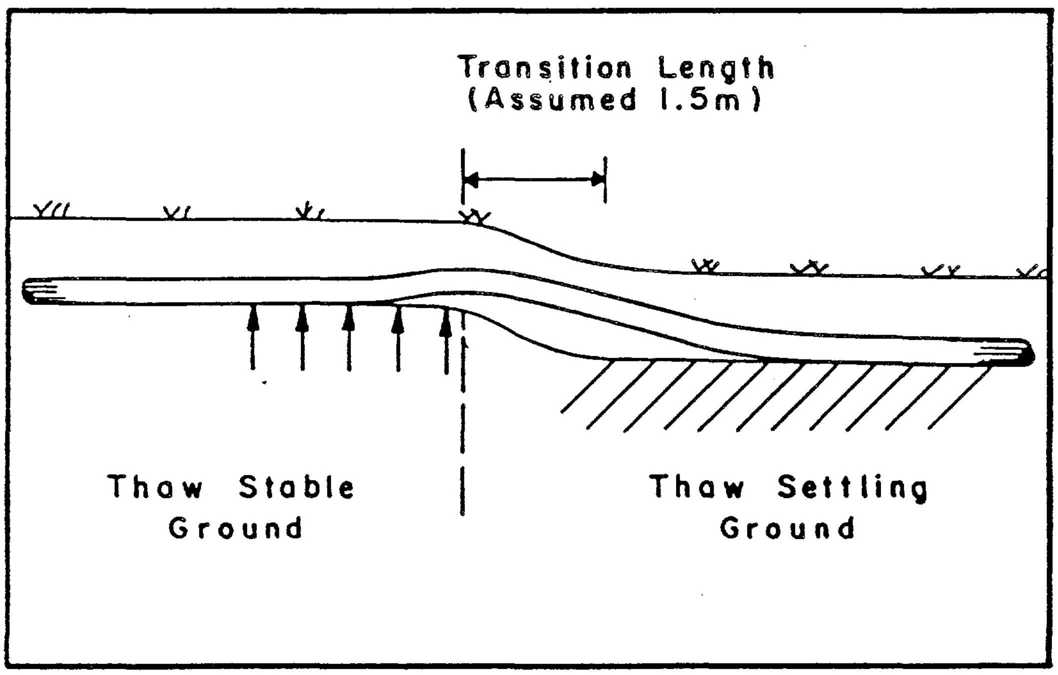


FIG.2 DIFFERENTIAL THAW SETTLEMENT

Frost Heave. Studies revealed that in general the frost bulb formed around a shallow buried pipe wall forms part of the larger layer of seasonal frost and that the overall stiffness would be sufficient to prevent excessive curvature. At some stream crossings and overland sections of deeper buried pipe the frost bulb around the pipe may not form part of the seasonal frost. Sag bends were identified as being particularly sensitive to this effect with potential for increasing the compressive strain in the pipe. Frost-heave potential at sensitive locations was evaluated and was used as input for stress analysis of the pipeline.

The analysis revealed that the critical strain was exceeded on tangent pipe adjacent to sag bends at the base of frozen slopes greater than 10^{o}. Consequently, the sag bends were insulated to prevent the formation of a frost bulb.

Slope Evaluation. The Norman Wells pipeline crosses a large number of slopes, many of which are susceptible to downslope movement as a result of thermal degradation. To analyze the stability of slopes and design a stable slope the following information was required:

1) slope height and angle
2) geology
3) strength parameters
4) geothermal and permafrost conditions
5) groundwater regime
6) seismic considerations

Office, field and laboratory programs were carried out to obtain the required parameters. Four modes of slope failure were considered in the analyses:

1) deep seated failure
2) infinite slope failure (whole slope)
3) infinite slope failure on a localized portion of the right-of-way
4) failure in the backfill around the pipe.

A list of 150 significant slopes was prepared. Significant slopes being those requiring site-specific stability analyses and design. Most of these slopes are located between Kp 0 and Kp 380.

Extensive analysis of slope stability resulted in a three-phase approach to slope evaluation as follows:

1. Design phase: determine which slopes are stable and establish practical mitigation for instability.

2. Construction phase: follow rigid clearing and construction specifications to minimize sensitive slope disturbances; evaluate and refine designs to reflect actual conditions.

3. Operational Monitoring phase: monitor slopes during operations, particularly in respect of geothermal conditions and groundwater regime.

From the geothechnical studies three mitigation concepts were developed:

1. Prevent thaw - for use in highly ice-rich slopes - In such a design thaw is restricted to the natural active layer.

2. Retard thaw - in certain slopes depending on angle and soil types or ice conditions, thaw advancement is permitted at a controlled rate.

3. Cut-Back Slopes - for unavoidable slopes that are sufficiently steep to be inherently stable, cutting back is required to ensure long-term stability.

The geotechnical studies revealed a significant relationship between the depth of thaw and width of clearing. Although on most of the route a 25 m right-of-way was cleared; on sensitive slopes a clearing width of 13 m was specified to retard thawing effects.

Studies led to the conclusion that wood chips would constitute a suitable insulation for thaw prvention or retardation. After intensive studies of the properties and performance of wood chips, approval was obtained for use. Depths ranging from 0.5 to 1.5 m have been specified for use on certain slopes.

Table 2 shows the slope design guidelines.

Pipeline Design

Various aspects of the design of the pipeline have been described in the A.S.M.E. paper 83-OMA-303 by Nixon, Stuchly and Pick (1984). The Oil Pipeline Regulations of the NEB specify requirements for the design and include requirement for compliance with Canadian Standards Association Z183-M1982.

The pipeline has been designed to withstand two types of loadings defined as primary and secondary. The former includes circumferential stress due to internal pressure, and this stress is limited to 72% of the specified minimum yield strength (SYMS) of the pipe by the CSA-Z183 pipeline code. The code further restricts the maximum shear stress resulting from internal pressure and thermal effects to 45% of SYMS. Secondary loadings which are displacement restrictive, such as those imposed by thaw settlement and frost heave, are limited by maximum allowable strain. Buckling analysis and maximum energy distortion criteria defined the maximum compressive strain at 0.5% in consideration of both primary and secondary loadings. This value allows a factor of safety of 1.3, discounting seismic effect.

The maximum allowable operating pressure (MOP) for the pipeline is 9930 kPa (1440 psi).

The temperature differential to be considered during design is the maximum difference between the temperature of the flowing oil and the thermally stress free reference temperature of the pipeline when laid in the ditch and backfilled. The temperature differential used in the stress analysis for the pipeline was selected to be $36^{o}C$ corresponding to a reference temperature of $-30^{o}C$ and maximum operating temperature of $+6^{o}C$.

Table 2
Norman Wells Pipeline Project
Slope Design Guideline (13 m Cleared Width)

Soil Type	No Mitigation	Mitigation: Slope Treatment	Mitigation: Select Backfill*
Ice Rich Clay	$< 9^{o}$ Stable	$>18^{o}$ Cut and insulate	$>4^{o}$
Ice Rich Till	$<13^{o}$ Stable	$>20^{o}$ Cut and insulate	$>7^{o}$
Ice Poor Till	$<18^{o}$ Stable	$>28^{o}$ Cut Back Depending on Height	$>10_{o}$

* On certain slopes where excavation was achieved with a wheel ditcher the cut-off angles for select material were increased.

As a result of the studies, differential thaw settlement values were established for various segments of the pipeline; 0.8 m for the first 78 km, 0.75 for 78 to 440 km and 0.70 for permafrost areas over the rest of the route. For areas of deep peat, design thaw settlements of 1.2 m were predicted. A transition length of 1.5 m was selected as conservative distance over which a transition could occur.

As a result of thaw-settlement loading analysis, an approval was obtained from the NEB to vary the general requirement for cover from 1.0 m to 0.76 m, resulting in reductions in pipe loading at transitions, and, consequently, a notable reduction in wall thickness of the pipe.

Pipe wall thicknesses are shown in Table 3.

<u>Stress Analysis</u>. It was determined that the governing factors in pipe design would be the structure response of the pipe to loadings caused by differential settlement and frost heave. Stress analysis was carried out using a three-dimensional finite-element computer program which considered both elastic and plastic deformation of the pipe.

Table 3
Design Wall Thickness for
Grade 359 kPa (52,000 psi) 0.76 m of Cover

Location kmp	Seismic Zone	Case	Design Thaw Settlement mm (in)	Soil Loading Thaw Stable/ Settling Side kN/m (lbs/ft)	Design Wall Thick. mm (in)	Operating Strain of 0.5% Temp. Diff. °C (°F)	Max. Axial Strain (%)
0 - 78 kmp	A	A	.80 (32)	7.3/3.7 (500/250)	7.16 (.282)	36.1 (65)	.497
78-440 kmp	A	B	.75 (30)	7.3/3.7 (500/250)	6.91 (.272)	36.1 (65)	.496
440-478 kmp	A	C	.70 (28)	6.4/3.2 (440/220)	6.35 (.250)	36.1 (65)	.499
478-868 kmp	B	D	.70 (28)	6.4/3.2 (440/220)	6.35 (.250)	36.1 (65)	.499

Pump Station Design

The optimal initial configuration of pumping capacity called for three pump stations along the pipeline, allowing for future expansion of capacity if needed by the addition of three intermediate stations.

Fuel cost considerations call for operation of the Norman Wells pump station at or near MOP in order to maximize power input at lowest fuel costs. The next priority for pumping is at the third pump station south of Fort Simpson with the Wrigley pump station being used only as required to maintain throughput.

Pump stations were designed with two 100% units; one for back-up. The Norman Wells station is powered by dual-fuel engines (Natural Gas-Propane); the other two stations are diesel fueled with fuel being either trucked or barged to storage.

Pump Drivers at each station are as follows:

Norman Wells:	2 @ 721 kw (970 HP)
Wrigley:	2 @ 245 kw (330 HP)
Mackenizie Highway	2 @ 561 kw (750 HP)

Sectionalizing Valves

Canadian Pipeline Regulations require the placement of mainline sectionalizing valves at a spacing not exceeding 30 km. Valve locations were determined to meet regulatory requirements while ensuring that spills resulting from line ruptures were minimized in sensitive areas. The use of remotely operated valves and a leak detection system to protect sensitive areas has been incorporated into the pipeline design.

All remotely controlled valves are operated by a radio controlled, thermal-electric/hydraulic-powered valve operators.

Communications

Communications planning has been divided into two phases, construction and operations. The principal requirments during construction were mobile voice communications for contractors and supervisory staff with outside services for the main camps.

During operations, communications requirements are to operate the supervisory control and data acquisition system (SCADA) and to provide mobile voice communications for maintenance and operating staff. Most data points on the pipeline were connected by UHF/VHF links to a repeater on an existing microwave tower. All remote valves and pump stations connect through an RTU by microwave link to a master computer in the Norman Wells operation centre.

ENVIRONMENTAL CONSIDERATIONS

As mentioned previously, during the regulatory-approvals stage the Company performed a significant number of studies and submitted the resulting reports for regulator and intervenor review and critical comment.

The principal issues identified during the studies included terrain disturbance in permafrost, wildlife conflicts, particularly moose and raptors (birds of prey) and furbearers species. IPL has implemented a progressive wildlife-management policy allowing for compensation of hunters or trappers adversely affected by the pipeline.

Extensive archaeological surveys were conducted along the right-of-way prior to construction and the few significant sites identified have been clearly protected.

From its environmental studies and plans, IPL developed an ongoing program for the environmental education of all project staff including contractors personnel. The indoctrination of all personnel in respect of the environmental and socio-economic issues of the project is mandatory and is ongoing. An environmental inspection program was developed whereby each operation is scrutinzied to verify that the environmental protection commitments are being fulfilled.

To ensure that all project personnel understood the environmental-protection commitments, an environmental procedures manual was prepared and was incorportated as part of all contract documents for the project.

MONITORING

The Company has agreed to conduct an extensive monitoring program in cooperation with governments to verify that the predictions made are valid. The program focuses on the observation of terrain conditions, geothermal conditions, frost heave, thaw settlement, wildlife and habitat responses for periods sufficient to verify that equilibrium conditions have been established or that no significant disturbance has occurred.

The monitoring program calls for extensive instrumentation and observation on a regular basis for a minimum period of three to five years after construction. Aerial photography of the complete alignment will be done for five consecutive years.

CONCLUSIONS

After the first year of operation, it would appear that the Norman Wells pipeline met its objectives of environmental and socio-economic responsibilities.

Some ditch backfill settlement has resulted from melting of ice-rich material and/or loss of fibrous material during ditching operations. A two-year winter program is underway to ensure adequate pipe cover and minimize water erosion along the ditchline.

Winter maintenance uses either the right-of-way or winter roads but almost all summer mainline work requires helicopter support.

REFERENCES

Nixon, J.F., Stuchly, J., Pick, A.R., 1984 Design of Norman Wells Pipeline For Frost Heave and Thaw Settlement. 3rd International Symposium on Offshore Mechanics and Arctic Engineering, ASME Trans. of Journal of Energy Resources Technology, Paper No. 83-OMA-303.

NORMAN WELLS PIPE LINE PROJECT

BIBLIOGRAPHY

Burgess, M., J. Pilon & K. MacInnes. 1986. Permafrost Thermal Monitoring Program Norman Wells to Zama Oil Pipeline. Proceedings Northern Hydrocarbon Development Environmental Problem Solving conference, Banff, Alberta, Sept. 24-25, 1985.

McRoberts, E. C., J. F. Nixon, A. J. Hanna, A. R. Pick. 1985. Geothermal Considerations of Wood Chips used as Permafrost Slope Insulation. Proceedings for Fourth International Symposium on Ground Freezing/Sapporo.

Nixon, J. F., J. Stuchley, A. R. Pick. 1984. Design of Norman Wells Pipeline for Frost Heave and Thaw Settlement. 3rd International Symposium on Offshore Mechanics and Arctic Engineering, ASME Trans. of Journal of Energy Resources Technology, Paper No. 83-OMA-303.

Pick, A. R. 1987. Use of Wood Chips for Permafrost Slope Stabilization. CSCE Cold Regions Speciality Conference, Montreal.

Pick, A. R., R. H. B. Sangster, J. D. Smith. 1984. Norman Wells Pipeline Project. Proceedings: Cold Regions Engineering Speciality Conference, April 4-6, 1984. Canadian Society for Civil Engineering Montreal, Quebec.

Pick, A. R., J. D. Smith. 1985. Pipeline in Canada's far north in service. Oil and Gas Journal, August 19, 1985.

Pilon, J. A., A. P. Annan, and J. L. Davis. 1985. Monitoring permafrost soil conditions near a buried oil pipeline using ground probing radar and time domain reflectometry techniques. Extended abstract. 55th Annual International Meeting of the Society of Exploration Geophysicists, Washington, D. C., Oct. 6-10, 1985.

Smith, J. D., A. R. Pick, Air Pressure Testing of Norman Wells, NWT to Sarnia Pipeline. Seventh (1988) International Conference & Exhibition on Offshore Mechanics and Arctic Engineering, February 7-12, 1988. (Available March 1988)

Wishart, D. M. 1986. Reclamation of the Norman Wells Pipeline. Proceedings of the Boreal Institute for Northern Studies, Knowing the North Conference, Edmonton, Alberta, November 20-22, 1986.

Wishart, D. M. and C. E. Faux. 1985. Norman Wells pipeline project, right-of-way drainage control - problems and solutions. Proceedings of the Northern Hydrocarbon Development Problem Solving Conference, Banff, Alberta, Sept. 24-26, 1985.

/emc
January 18, 1988

EDWARD W. BEST

Born: Windsor, Ontario, 1927

Education:

B.Sc. (Geology), 1949, University of Western Ontario
Ph.D. (Geology), 1953, University of Wisconsin
Advanced Management Program, 1972, Harvard Business School

Business:

Partner, Foster Research (Management and Economic Consultants), Calgary, Alberta
Board of Directors and Compensation Committee, Triton Canada Resources Ltd., Calgary, Alberta
Board of Directors and Commodities Committee, NOVA Corporation of Alberta, Calgary, Alberta
Board of Directors and Diversification Committee, Fishery Products International Ltd., St. John's, Newfoundland
Board of Directors, Canada Development Corporation, Toronto, Ontario

Active Affiliations:

Advisory Board Chairman, International Centre at The University of Calgary
Board of Directors, Calgary Chamber of Commerce
Chairman, Independent Industrial Advisory Committee on Earth Sciences, Canada Energy, Mines and Resources
Advisory Board, Tyrrell Museum of Paleontology, Drumheller, Alberta
Chairman, Advisory Council on Competition Matters, Consumer and Corporate Affairs, Canada

Previous Significant Affiliations:

Board of Governors, Canadian Petroleum Association (Chairman 1983)
Board of Governors, The University of Calgary (Vice-Chairman 1979-1981)
Board of Directors, Banff School of Advanced Management
Board of Directors, Private Energy Research Association
Board of Directors, Coal Association of Canada
Board of Directors, Arctic Institute of Canada
President, Canadian Society of Petroleum Geologists
Chairman of the Board, Magnorth Petroleum Ltd.
Board of Directors and Audit Committee, ProGas Ltd.
Board of Directors and Executive Committee, Canterra Energy Ltd.

Previous Employment:

1955-1985, BP Canada Inc. (retired as President of Oil and Gas Division, and Director, BP Canada Inc.)