



## **GEOLOGICAL SURVEY OF CANADA**

### **OPEN FILE 5004**

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# **Frost heave and northern pipelines, state of the art and status of research—three contributing studies**

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Compiled by D.E. Lawrence, S.L. Smith and M.M. Burgess

2005

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**Frost Heave and Northern Pipelines  
State of the Art and Status of Research  
Three Contributing Studies**

Compiled by D.E. Lawrence, S.L. Smith and M.M Burgess

**2005**

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## **Foreword**

An application to build a large diameter buried chilled natural gas pipeline to transport Mackenzie Delta gas through the Mackenzie valley to southern markets was filed in October 2004. The frost heave issue that was vigorously debated for similar gas pipeline proposals in the late 1970s is once again relevant.

In view of this renewed interest, three review studies on frost heave and pipelines were commissioned by the federal government, under the scientific authority of the Geological Survey of Canada (GSC) of Natural Resources Canada, in 2004. The aim of these studies was to document the current state of knowledge about frost heave theory, testing and predictive modelling, and the application of this knowledge to the design, construction and operation of a buried chilled gas pipeline. These reports were also intended to support the regulatory review process.

This Open File first provides a summary overview of the three studies followed by the individual commissioned reports.

Note: The opinions expressed in these reports are those of the authors and may not necessarily agree with those of the GSC

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March 2005

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**Part 1.**  
**SUMMARY**

**Frost Heave and Northern Pipelines  
State of the Art and Status of Research  
A Summary of Three Studies**

by

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March 2005

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## INTRODUCTION

The Berger Commission (1977) and the National Energy Board (1977) issued their decision reports on natural gas pipeline proposals from the Alaska-Beaufort region in 1977, effectively postponing any construction for an indefinite length of time. One of the central technical and engineering design issues that was debated for these gas pipelines was frost heave. The development of a frost bulb around buried chilled pipelines, associated (differential) heave of frost-susceptible soil and resultant stresses imposed on the pipeline must be considered in the design of northern gas pipelines. By the early 1980s interest in the construction of a large diameter northern gas pipelines had declined. The Norman Wells to Zama oil pipeline was built in the mid 1980s. The design of this small diameter buried ambient temperature pipeline, which has operated successfully for 20 years in the Mackenzie valley, had to contend principally with thaw settlement. Interest in frost heave research and the refinement of prediction models, however, has continued in these intervening years, but not at the feverish pitch of the late 1970s.

An application to build a large diameter buried chilled natural gas pipeline to transport Beaufort/Mackenzie Delta gas through the Mackenzie valley to markets in southern Canada and the USA was filed in October 2004. The frost heave issue that was vigorously debated for similar proposals in the late 1970s is once again relevant. In unfrozen terrain within the continuous permafrost zone (such as under water-crossings), and within the discontinuous permafrost zone where transitions from frozen to unfrozen terrain are numerous, differential heave is of particular concern.

In view of this renewed interest, three review papers on frost heave and pipelines were commissioned by the federal government, under the scientific authority of the Geological Survey of Canada (GSC) of Natural Resources Canada, in early 2004. The aim of these studies was to document the current state of knowledge about frost heave, predictive modelling and the application of this knowledge to the design, construction and operation of a buried chilled gas pipeline. The results of these studies are contained in three reports; parts 2, 3 and 4 of this Open File:

- Part 2. State of the art paper on frost heave – a review of frost heave theory and models, by EBA Engineering Consultants Ltd, Edmonton
- Part 3. Review of large scale northern pipeline test facilities, by J.I. Clark and Associates, St John's
- Part 4. Review of centrifuge testing applicability to frost heave, by C-Core, St John's.

## HIGHLIGHTS OF REPORTS

1. **State of the art paper on frost heave – Review of theory and models (Part 2)**
- 2.

This report reviews the development and current state of knowledge of frost heave theory and predictive models for frost heave, both in general and as applied to buried chilled gas pipelines. It highlights the significant milestones in the development of each. Data requirements for predictive models are also examined. The concluding sections of the report summarize the state

of the art, examine outstanding issues and make recommendations for further research. Details on most of the significant models and experiments are provided in tabular form allowing convenient comparison of the salient assumptions and findings in appendices to the report. They include:

- A. small scale frost heave experiments,
- B. frost heave prediction models and
- C. frost heave prediction models for buried chilled gas pipelines.

Appendix D lists the principal institutions and researchers involved in frost heave research. An extensive reference list is provided on frost heave theory and predictive modelling.

The report states that during the 1980s and 90s there was further refinement of frost heave theory and a number of significant findings arose from laboratory experiments. Although no funding was available for large scale work, significant progress was made in frost heave prediction modelling in the period from 1980 to 1995 including Konrad and Morgenstern (1980, 1981, 1982), Shen and Ladanyi (1987), Fremond and Mikkola (1991), Nixon (1992) and others (see Table 3 in Appendix A). Published models currently in use in North America are Nixon (1991), Konrad and Morgenstern (1980), and Guymon (1993). Researchers in the UK, Sweden, France and Finland also have published frost heave prediction models. All authors claim successful predictions. Companies and consortia have developed other models but they are proprietary and not available in the literature.

The most recent developments directly applicable to chilled pipelines are: the discrete ice lens model of Nixon, (1992); the 2 dimensional rigid ice model of Shah and Razaqpur (1993); and the development by Selvadurai et al. (1999) of a 3 dimensional hydrodynamic model based principally on the work of Shen and Ladanyi (1987). (For citations listed in here refer to part 2 of this Open File)

The report states that a comprehensive analysis of the pipeline/frost heave problem must consider the following:

- Coupled heat flow and moisture transport in frozen and unfrozen soils
- Mechanical behaviour of unfrozen soil especially in response to freezing and heave
- Moving boundary problems associated with a moving freezing front and frost heave
- Growth of pore ice and ice lenses
- Mechanical behaviour of the buried pipe including structural response of the pipeline
- Pipeline-soil interface behaviour.

In addition the design of a buried chilled gas pipeline would have to consider:

- An upper bound estimate of the differential movement and stresses imposed on a pipeline subjected to frost heave and other processes
- The level of accuracy in frost heave prediction required to safely construct and operate a buried gas pipeline
- A thorough review of differential frost heave effects mitigation measures
- A thorough review of pipeline materials and their ability to withstand stresses generated by differential heave

- An evaluation of pipeline construction techniques that can limit the differential frost heave stresses
- An extensive monitoring program during pipeline operation.

The report also emphasized that the predicted frost heave generated by any model is directly dependant on reliable input data from a number of sources. Some data are derived from **laboratory testing** of soil samples, including determination of segregation potential, hydraulic conductivity and unfrozen water contents. Information on soil thermal conditions and climatic data must be gathered in the field as a part of **long term monitoring** programs. In addition **site investigations** that include soil sampling, field and lab testing, geophysical instrumentation and surveying are required to determine the engineering and thermal properties of the soils.

The report presents a summary of the current state of knowledge, highlighting the following:

- Considerable information has been published on frost heave since the late 1970s
- Small scale laboratory frost heave tests have limitations due to rapid freezing, large thermal gradients, short test duration and limited sample size
- Large scale laboratory and field tests have been used to evaluate scale effects
- Centrifuge testing has been able to deal with testing time constraints
- Research on frost heave prediction for buried chilled pipelines has increased since 1980
- Accurate frost heave prediction is in the advanced research stage and provides conservative estimates of the upper bounds of frost heave enabling the safe design of chilled gas pipelines
- The most difficult aspect of frost heave prediction is the acquisition of the input data
- Various numerical models with different levels of simplification exist that are generally variations of the same equations. Complete models include stress analysis. Practical models are often non-mechanistic deterministic models. Older and simpler models that predict differential heave around a chilled pipe provide a conservative upper bound estimate of frost heave and stress which is required for safe pipeline design.

Recommendations for further work include:

- A thorough elementary examination of the driving force of frost heave
- Development of a method to measure the hydraulic conductivity in the frozen fringe
- Development of a database of frost heave test results
- Standardization of frost heave test procedures and equipment
- Development of a method to indirectly measure pressure at the location where a new ice lens forms
- A three dimensional frost heave prediction model based on Miller's rigid ice model, Shen and Ladanyi's model or Nixon's discrete ice lens theory, including the extensive stress analysis such as that given by Shen and Ladanyi (1987)
- Commercial development of such a model
- Clear statements of the input parameters required for each frost heave prediction model. Access to the computer code is often required to list these input parameters
- An overview of frost heave prediction for buried chilled gas pipelines, that includes a discussion of pipeline mechanics.

### **3. Review of large-scale northern pipeline test facilities (Part 3)**

This report presents a review of 10 (Alaska 3, Alberta 2, NWT 3, Yukon 1 and France 1) large or full-scale pipeline test facilities constructed and operated to investigate the effects of pipelining in northern regions. Testing at these facilities was initiated in response to pipeline proposals in the Mackenzie Valley in the 1970s. The principal area of interest was frost heave and pipe-soil interaction, however tests and observations on other aspects were also important including thaw settlement, permafrost degradation, materials performance, remediation techniques, and design options.

The report provides a chronology of large-scale pipeline testing and the corporate players and consortia with an interest in the test sites from 1970 to 1992. A detailed description of each facility, including its configuration, principal tests, purpose and significant findings is provided. Because the test sites were corporately run and financed (except Caen, France, which was principally a joint effort for the French and Canadian governments and later received industry support), the results were at one time proprietary. However, while some of the information is still unavailable to those outside the sponsoring organizations, much of the information is now available in the public domain.

The report states that the results of large-scale testing provide a range of data related to frost heave that would be useful in the continued study of northern pipelines.

The Calgary Alberta test site provides the best data set relating to frost heave of a large diameter chilled pipeline buried in natural unfrozen soil. Four tests were conducted in unfrozen natural soils. Important conclusions from the results of the Calgary experiments were that heave rate and total heave can be reduced by increasing burial depth and that heaving of already frozen soils is negligible.

The Caen experiments provide data on a small diameter pipe under controlled conditions of freeze and thaw as well as more controlled soil and moisture conditions than at other facilities. A 27.3 cm diameter pipe, 18 m in length, was buried at a depth of 33 cm in an enclosed, controlled environment facility. Studies were carried out, on the behaviour of freezing soils and the deformation of a pipe across an interface of non frost-susceptible sand and a highly frost susceptible silt, in a controlled environment. These tests provide data on frost penetration and thaw; frost heave and thaw settlement for soils and pipe and the stresses induced in the pipe due to pipe curvature during a number of freeze thaw cycles. The data has been extensively used in the development and calibration of numerical prediction geothermal and frost heave models. Tests were also performed on a pipe laid across a frozen/unfrozen interface but issues related to thaw of the frozen side at depth made interpretation difficult.

At Fairbanks, Alaska, two test sites were developed in the 1970s and 1990s. The earlier tests included several ditch and insulation configurations. Little information is available in the public domain on the results for this work. The site was revitalized in the 1999 with the investigation of pipe movement at a frozen/unfrozen interface.

At the Mountain River/Sans Sault Rapids, NWT, site a large diameter pipe section buried at a depth of 2.5m and operated in a chilled mode for 2.25 years showed no significant movement. In sections subjected to temperature cycling there was extensive thaw and settlement. Highly disturbed portions of the site showed a large increase in the active layer thickness and ponding of water.

The Norman Wells chilled gas test site ran a number of chilled and warm, buried and bermed test sections in ice rich frozen soils. Data on bermed sections indicated that there was very little settlement of a chilled pipe and that active layer thickness increased according to the degree of disturbance.

At several test sites temperature sensors were utilized to monitor the geothermal regime both in the soils surrounding the test pipe and in areas outside the influence of the pipe. Ground thermal measurements indicated that the pipe temperature rather than the ambient ground conditions controlled the thermal regime below the pipe. These temperature data are useful in assessing the predictive capability of geothermal assessment tools. Data on pipe-soil interaction during heave and settlement are available from the Caen and Fairbanks sites.

In addition to tests on chilled pipes, some facilities directed their attention as well or exclusively to other frozen terrain/pipeline issues. At some sites, tests on construction and land reclamation techniques were carried out, including trenching and other excavation methods, snow road and working pad performance and revegetation techniques. The Inuvik, Northwest Territories site provides the most comprehensive data on thaw settlement of pipelines in ice-rich soils. The Quill Creek, Yukon, site provides good information on the performance of mitigative measures to control thaw and settlement for three warm pipe modes. At the Nordegg, Alberta, site, testing was conducted to determine soil thermal properties, the data being used for the prediction of the thermal regime around a warm pipeline.

According to the report's author, large scale testing demonstrates that permafrost can be preserved below a chilled gas pipeline and that by increasing the trench depth (burial depth) the amount of frost heave can be reduced to tolerable limits. As well, construction and operation can be successfully carried out for a large diameter chilled pipeline i.e. ditching to the desired depth is feasible in permafrost using conventional ditching machines modified for northern use.

However, a number of issues have not been fully addressed and would require careful consideration for future pipelines including drainage and erosion control methods the behaviour of a chilled gas pipeline below a river crossings and slope stability.

The author makes a single recommendation for further study that is directly related to frost heave: several proprietary predictive models exist, and one or two in the public domain. However, none take into account consolidation or plastic deformation below the frost bulb. This could be significant in soft or organic soils. Studies on soil consistency and heave would be useful.

### **3. Review of centrifuge testing applicability to frost heave (Part 4)**

This report summarizes the applicability of centrifuge testing to northern pipeline frost heave design, and discusses the advantages and limitations of this technology. The reduced scale, accelerated timeframe and cost effectiveness of centrifuge testing provides an opportunity to extend this generally accepted tool for soil-structure research, to the modelling and prediction of frost heave, as it applies to the design and operation of arctic pipelines. The technique is also advantageous where the cost of large-scale testing would be prohibitive.

In 2001-02 C-CORE undertook a series of centrifuge modeling tests to determine if the results of full-scale testing at the Calgary test site could be replicated. This work led to additional research both for the GSC and industry. Currently (2004) work is being carried out by C-CORE for the Gas Research Institute and Trans Canada Pipelines. The objective of this work is to further evaluate centrifuge technology as a tool in predicting the effects of frost heave and investigating pipeline behaviour under a range of conditions including soil type, pipe burial depth, soil and pipe temperature and supply of water to the freezing front. The results of this work however will be proprietary.

Although there are limiting factors in the applicability of centrifuge testing and its applicability to frost heave and pipelines, there is a general consensus that the soil parameters including grain size, void ratio, temperature, confining stress and permeability can be accommodated.

The author indicates that because of modeling and scaling limitations and the fact that a centrifuge test is an independent physical event it may not provide an ideal simulation of the conditions under consideration or replicate the exact field conditions. It may however provide valuable insight into the problem being investigated and its engineering implications. In order to validate centrifuge test data, it is suggested that rather than rely on a specific test for a solution, it is better to consider a “modeling of models” approach. That is, conduct a number of tests using a range of scales to see if the results are in agreement with each other. As well it is wise to validate the results of centrifuge modelling with other physical or numerical models.

The report states that there is good agreement between results from centrifuge testing and the Calgary test site data, revealing similar patterns with respect to heave displacements and time. Comparison of pipeline heave data (Fig. 8, Part 4) for Calgary and model tests, indicates that there is indeed a very close agreement between centrifuge testing and full scale test data from the Calgary Deep Burial Site. However, comparisons of the Calgary Control Site reveal a wide disparity between centrifuge and full-scale test results, with heave in the full-scale test indicated at 30 to 60% greater than that from centrifuge testing.

There seem to be relatively good agreement between heave rate vs. pressure for Calgary and centrifuge data (Fig. 10, Part 4) indicating that heave may be limited by increasing burial depth.

The report also states that displacement is similar for the model and prototype, however comparison of displacements (Table 3, Part 4) for the restrained pipe section at the Calgary site indicates for the 86 day test 40% more heave in the model and in the 135 day test approximately 10% less heave in the model than in the Calgary prototype. As well comparisons of loading

show a wide disparity. These conclusions are not entirely supported by the data/results presented and many field situations have not yet been replicated and tested, such as heave and deformation occurring at unfrozen/frozen interfaces.

The report states that there is potential for centrifuge testing as applied to frost heave testing and that:

- Centrifuge modeling linked with simple analytical techniques can be used for efficient design of pipelines for the effects of frost heave
- Emphasis should be placed on demonstrating the repeatability of test data and their validation, including modeling of models of the effects of chilled buried pipelines and comparisons with accepted numerical models
- There is a need for three-dimensional modelling of pipe-soil interaction effects i.e. across a frozen-unfrozen boundary
- A semi-empirical model is emerging from the work on actual heave measurements of pipelines and centrifuge tests
- A relationship has been developed between the rate of heave and pressure on the freezing front, which reflects the initial burial depth and the penetration of the freezing front with time
- A possible design methodology that establishes risk and reliability could be refined over the next couple of years. It would need to include or consider the following, some of which integrate the results of centrifuge testing:
  1. Establish a suite of frost heave design curves for a range of soils types and conditions using centrifuge tests
  2. Estimate the distribution of unfrozen soils along the proposed pipeline route
  3. Establish engineering design criteria for specified limit states through a variety of methods
  4. Assess the system reliability for each limit state and define failure consequences
  5. Establish pipeline burial depth for each design unit based on the risk based approach

Concluding remarks include the following principal points:

- Centrifuge testing is a quick, widely accepted and cost effective method of testing and analyzing geotechnical systems and an opportunity exists to extend its use to the prediction of frost heave and the design of arctic pipelines.
- Centrifuge testing does not provide a perfect simulation of prototype conditions but provides useful engineering insight
- Modelling of models technique should be used to validate test results
- Comparisons of centrifuge test results and the Calgary full-scale test results reveal similar soil and pipe behaviour
- There is no suitable publicly available numerical model or operating chilled pipeline that can be used to extend the comparisons. Comparisons with full-scale behaviour are required to verify the models
- A semi-empirical design method is emerging from current centrifuge testing that includes the relationship between the rate of heave and pressure at the freezing front. Centrifuge modelling could be expanded to include considerations of various pipe geometries, burial configurations, soil types, and geothermal and hydrological conditions

- A combined approach using centrifuge modelling, numerical analysis and limit state design methods would provide a cost-effective method to define the frost heave behaviour of a pipeline
- Current knowledge of centrifuge tests suggests “that it may be suitable for use as a design tool and to investigate the effects of various operational strategies”.

In addition, the above comments are supplemented and supported by an independent study carried out by Haigh which is included in this report:

- Previous centrifuge modelling of frost heave suggests that this is an area of considerable promise –good correlation having been achieved between full-scale and centrifuge experiments
- Scaling of frost heave is not completely understood
- Complex issues including creep and the growth of ice crystals have not been fully resolved
- Results of centrifuge tests on frost heave of pipelines give a valuable insight into soil and pipe behaviour, and could be developed into a useful design tool
- To achieve confidence in centrifuge results validation involving various methods would be required.

## **SUMMARY**

The three reports provide insight into the progress made on frost heave related to arctic pipelines. They identify some of the areas where additional work can be undertaken to improve frost heave prediction and cost-effective design and operation of chilled gas pipelines in the arctic environment. The reports also point out the critical inputs required for the prediction of frost heave and its effects on a pipeline.

A range of models and /or experiments may be used to study the frost heave process. These range from small bench scale experiments to more sophisticated numerical models:

- Small bench scale frost heave tests/experiments – small samples, large temperature gradients and short time periods
- Large/field scale experiments – closer to field size, more natural soil and moisture conditions, more realistic gradients and time (vary from controlled environment like Caen and more natural situations such as Calgary)
- Centrifuge experiments – scale models, reduced time due to increased gravity, overcome some of the problems related to bench scale tests and are less expensive than large scale experiments
- Numerical models – various types with different levels of simplification but generally variation of same equations. Complete models include stress analysis. Practical models often non-mechanistic deterministic models.

These reports indicate that significant progress has been made since the 1970s. Models have been refined and more sophisticated testing has been carried out. Centrifuge testing, an accepted method for geotechnical testing has been initiated for frost heave modeling. The results of full scale testing from industry and government test sites have been useful in validating new models and test results. Although there is general agreement about the progress that has been made and

an increased level of engineering confidence that a chilled gas pipeline could be successfully designed, built and operated in northern Canada, there is still considerable work that can be done.

The EBA report (Part 2) that concentrated on a review of theory, modelling and laboratory testing indicates that we are in the “advanced stages of research”. This means that there is a fairly good understanding of the phenomena and its behaviour and effects. Centrifuge testing also shows considerable promise as a design and predictive modelling tool. Although there are significant limitations to both laboratory and centrifuge testing, there is a confidence that the predictive models derived from these test data would be applicable to the design and operation of pipelines and related facilities. This optimism however must be tempered by the fact that we have little experience with the behaviour of an operating pipeline that uses this knowledge in its design, operation and contingency strategies to deal with frost heave and its effects.

In effect regulators may be faced with making a decision on the use of relatively new and untested designs and technologies in a relatively unfamiliar and hostile environment, which have not been subjected to the rigours of operational experience. Under these circumstances it likely will be necessary to develop procedures and protocols to ensure the efficacy of a frost heave design i.e. stringent monitoring and contingency planning.

Both the EBA and C-Core reports (Parts 2 and 4) stress the importance of input data for the refinement of models and for design parameters. One of the greatest factors controlling the efficacy of modelling is the accuracy and validity of input data. Much of these data relate to natural soil materials and their behaviour, local and regional ground thermal, groundwater and hydrological regimes and as well climatic conditions. Some of these data can be gathered immediately prior to construction by the project proponent however, much of the input data on soil parameters, geothermal regime, hydrology and their probable evolution during the operational lifetime of a pipeline are best derived from the more long-term, *in situ* collection of field data. Traditionally this work has been the responsibility of government agencies.

The C-Core study indicates that centrifuge testing for frost heave prediction and pipeline design modelling shows great promise providing a cost-effective alternative to full-scale testing. However it is less advanced than other types of testing. Their frost heave/pipeline program initiated in 2001, concentrated on validation and comparison with the results from the Calgary test site. Subsequent work has been largely of a propriety nature. There is a need to validate centrifuge modelling with a full-scale operating situation. Despite this, it nonetheless provides important engineering information.

The findings of the three studies are generally in accord with the results of a survey conducted by the GSC in 2003 on the state of preparedness for the construction of a northern gas pipeline (Lawrence, 2004). The general consensus of numerous permafrost experts from across Canada was that generally progress has been made in addressing the issues identified in the 1960s and 70s and we have benefited from an expanding knowledge base derived through the experience gained from the construction and operation of other northern projects. However, there is a need to revisit many (some say almost all) of the basic issues and problems identified earlier. Continued research is also needed to update them for different geographical regions, design scenarios and engineering issues.

As well there is a need to design for the long-term viability of facilities under changing conditions and a requirement to continue to compile baseline data (thermal and geotechnical) for input into models and to facilitate design of pipelines. Unless design elements and construction procedures adequately contend with permafrost issues and associated climate change implications for a high-pressure gas pipeline, a project would be at risk. Engineering solutions to technical and environmental issues must be assured. These solutions must also be cost effective and regulators must be assured of the long term viability, safety and security and of the project.

Design of a buried chilled gas pipeline for the arctic will be contingent on the results of continued testing, refinement of existing models, the availability of good quality and reliable input data and the validation of models with full scale operational situations. Safe pipeline operation will depend on the ability of the pipeline operator and regulatory authorities, in the face of unknown or unproven design elements or construction procedures, to put in place monitoring systems and adaptive management strategies to ensure that the pipeline behaves as predicted.

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**Part 2.**

**State of the art paper on frost heave – a review of frost heave theory and models,**

**by EBA Engineering Consultants Ltd, Edmonton**

**June 2004**

# State of the Art Paper on Frost Heave

## Government of Canada's Northern Pipeline Preparedness Program



**Submitted to: Terrain Sciences Division  
Geological Survey of Canada, Natural Resources Canada**

June 2004  
Project No. 1100051

**EBA ENGINEERING  
CONSULTANTS LTD.**



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**STATE OF THE ART PAPER  
ON FROST HEAVE**

**Project No. 110051**

**JUNE 2004**

**STATE OF THE ART PAPER  
ON FROST HEAVE**

Submitted To:

TERRAIN SCIENCES DIVISION  
GEOLOGICAL SURVEY OF CANADA  
NATURAL RESOURCES CANADA

Prepared by:

EBA ENGINEERING CONSULTANTS LTD.  
EDMONTON, ALBERTA

Project No. 1100051

JUNE 2004

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## EXECUTIVE SUMMARY

EBA Engineering Consultants Ltd. (EBA) was retained by the Terrain Sciences Division of the Geological Survey of Canada (GSC) to develop a state-of-the-art paper on frost heave.

A technical review of a proposed pipeline in the Mackenzie Valley, NWT, must consider whether frost heave is understood sufficiently and can be controlled or limited to such an extent that safe construction and operation of a large diameter chilled gas pipeline is possible. This state-of-the-art paper on frost heave provides a thorough review of frost heave theory, prediction models, acquisition of input data for prediction models, validation of theory and models by laboratory experiments, and applicability of frost heave theory, prediction models and laboratory experiments to northern pipeline design and operation.

The number of publications on frost heave has increased considerably since the Berger inquiry in the 1970's. Frost heave theory developed by Miller 1978 has been proven in laboratory experiments and is accepted widely. The rapid freezing, associated large thermal gradients, short test duration, and limited sample size have been recognized as limitations of small scale laboratory frost heave tests. Large scale laboratory and field frost heave tests have been used to evaluate scale effects. In addition, scaled frost heave tests in centrifuges have dealt with some of the testing time constraints.

All current frost heave prediction models describe a set of variations of the same equations such as Fourier's law, the heat continuity law, Darcy's law, the mass continuity law, the Clausius-Clapeyron equation, and a frost heave criterion. These sets of equations are described for the frozen zone, the frozen fringe and the unfrozen zone of the freezing soil profile. A complete frost heave prediction model includes a stress analysis that describes elastic and viscous behaviour by Hooke's law and either the Norton-Hoff or Prandtl-Reuss law, respectively. Most researchers and practitioners who proposed frost heave prediction models claimed successful and accurate predictions, validated by small scale and large scale laboratory tests.

Frost heave prediction for buried chilled gas pipelines must consider all elements of the preceding paragraph, moving boundary problems associated with a moving freezing front and frost heave; mechanical behaviour of the buried pipeline, which includes the structural response of the pipeline to soil freezing; and interface conditions at the soil-pipeline interface. The soil must be modelled as a 2D or 3D continuum. A coordinate system and finite element

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discretization must be used which accommodates the complex coupled heat and water flows and displacements that accompany the ice lenses in a pattern influenced by the cooling from the soil surface and pipeline. The mechanical behaviour of the buried pipeline must be represented as a cylindrical shell which can possess complex non-linear stress-strain-time phenomena. Pipeline-soil interface behaviour must be described by interface phenomena such as frictionless contact, frictional contact or bonded contact and interface constitutive models determined from experiments.

Frost heave prediction models require input data such as climatic data (temperature, precipitation snow cover thickness); soil properties (e.g. soil moisture content, particle size distribution, Atterberg limits, salinity and organic content), thermal soil properties, segregation potential, hydraulic conductivity, and unfrozen water contents. The most critical input parameter for frost heave prediction models is the hydraulic conductivity of the frozen fringe. The hydraulic conductivity of the frozen fringe is difficult to determine. A procedure proposed by Konrad and Morgenstern 1980 to characterize frost susceptible soil in small scale laboratory tests in terms of their segregation potential describing the flow of water through the frozen fringe without knowledge of the hydraulic conductivity is used in many applications. The frost heave prediction model input data can be obtained from weather stations, site investigations along proposed pipeline route; laboratory index testing, ditch wall logging, geophysical programs, instrumentation (including thermistors), small scale laboratory frost heave tests, and laboratory TDR tests.

Frost heave research continues at several institutions and companies in countries such as Canada, USA, UK, Sweden, Finland, Russia, Japan and China. Safe design of buried chilled gas pipelines in cold regions could benefit if some of these research activities were focussed on: a thorough elementary examination of the driving force of frost heave; development of a method to measure the hydraulic conductivity in the frozen fringe; development of an extensive database of frost heave test results; standardization of frost heave test procedures and equipment; development of a method to indirectly measure pressure at the location where a new ice lens forms; development of a three dimensional frost heave prediction model based on the rigid ice model of Miller (1978), the model of Shen and Ladanyi (1987) or the discrete ice lens theory of Nixon (1991), including an extensive stress analysis such as given by Shen and Ladanyi; commercial development of such an advanced practical model; clearer listings of the input parameters required for each frost heave prediction model (access to the computer code is often required to list these input parameters); and an overview of frost heave prediction for buried chilled gas pipelines that includes discussion of pipeline mechanics. These suggested research

activities are not necessary requirements for safe pipeline design and serve academic, clarifying and informative purpose.

Design of a chilled buried gas pipeline must consider the following:

- An upper-bound estimate of the differential movement and stresses imposed on a pipeline due to frost heave and other processes;
- An assessment of the level of accuracy in frost heave prediction required to safely construct and operate a buried chilled gas pipeline;
- A thorough review of (differential) frost heave effects mitigation measures;
- A thorough review of pipeline materials and their ability to withstand stresses generated by differential frost heave;
- An evaluation of pipeline construction techniques that can limit differential frost heave stresses; and
- An extensive monitoring program during pipeline operation.

The quality of frost heave prediction models for buried chilled gas pipelines can only be fully assessed based on their performance and accuracy in predicting the stress-strain behaviour of soil and pipelines in large-scale laboratory and field experiments.

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## 1.0 INTRODUCTION

### 1.1 Background

The increase of the natural gas price over the last decade, combined with the expiry of oil and gas pipeline construction ban as a result of the Berger inquiry in the mid 1970's, prompted a renewed interest in oil and gas development in the Beaufort Sea/Mackenzie River Delta in the Northwest Territories, Canada. Natural gas producing companies with leases in the Beaufort Sea/Mackenzie River Delta are currently gathering information required for the design of a natural gas pipeline from the Beaufort Sea/Mackenzie River Delta. Construction and operation of a long pipeline is a major project with many technical, environmental, and socio-economic aspects. The pipeline proponents have to comply with current regulations to obtain permits for the pipeline construction and operation. Current legislation includes a federal environmental impact review process in which pipeline proponents need to submit documentation in which the technical, environmental, and socio-economic aspects associated with pipeline construction and operation are addressed, followed by public hearings. Pipelines in which natural gas is transported must be buried for security reasons and for protection of the northern environment (Ladanyi and Lemaire 1984). The Government of Canada has initiated a northern pipeline preparedness program in anticipation of an expected northern natural gas pipeline proposal. The Terrain Sciences Division of the Geological Survey of Canada (GSC), a branch of the Department of Natural Resources Canada, will be involved during the permitting process in the review of technical aspects of pipeline construction and operation.

Thermal degradation in areas with widespread to continuous permafrost conditions is limited by transporting the natural gas as a liquid, by maintaining a high pressure and subzero temperature in pipelines. One of the technical aspects associated with a chilled buried gas pipeline is how differential frost heave affects the integrity of the pipeline. A buried pipeline transporting gas at subzero temperatures generates a frost bulb around the pipeline. Spatial variability of the amount of ice formed in the soil along the pipeline will result in differential frost heaving and differential stresses in the pipeline. Differential frost heave occurs at soil type transition zones or at frozen – non-frozen soil interfaces. A technical review of a proposed Mackenzie Valley pipeline must consider whether frost heave is understood sufficiently and can be controlled or limited to such an extent that

safe construction and operation of a large diameter chilled gas pipeline is possible. For such an assessment, the GSC seeks to obtain information on the following aspects of frost heave:

- theory, prediction models, acquisition of input data for prediction models, validation of theory and models by laboratory experiments, and the applicability of frost heave theory, prediction models and laboratory experiments to northern pipeline design and operation;
- stress-strain behaviour of soil and pipe and frozen/freezing soil pipe interaction observations in large/field scale tests and experiments in controlled and natural environments undertaken by industry and government;
- use and applicability of centrifuge testing for frost heave assessment and pipeline design;
- experience in mitigation of frost heave in operation of pipeline and associated facilities in Canada and Alaska; and
- experience in mitigation of frost heave in operation of pipeline and associated facilities elsewhere, e.g. in the former Soviet Union, and their applicability to the design of a large diameter Mackenzie Valley gas pipeline.

The GSC solicited the opinion of a number of experts to acquire this knowledge, as part of the Government of Canada's northern pipeline preparedness program. EBA Engineering Consultants Ltd. (EBA) was asked to address the first aspect.

## **1.2 Scope of Work**

The scope of work for this assignment is to develop a state-of-the-art paper on frost heave. The state-of-the-art paper provides a thorough review of frost heave theory, prediction models, acquisition of input data for prediction models, validation of theory and models by laboratory experiments, and applicability of frost heave theory, prediction models and laboratory experiments to northern pipeline design and operation.

## **1.3 Methodology**

Published state-of-the-art papers on frost heave were firstly reviewed. These state-of-the-art papers were written by several engineering practitioners and scientists during the last few decades: Miller 1980, O'Neill 1983, Smith 1985, Nixon 1987, Kay and Perfect 1988

Ladanyi and Shen 1989, Black and Hardenberg 1991, Konrad 1994, Black 1995, Jones 1995, Kujala 1997, and Henry 2000.

This review was followed by a comprehensive literature search on the development of frost heave theory. Innovations and shortcomings of theories and challenges to the proposed theories are briefly addressed concluding with a description of the current state of frost heave theory and our confidence level in the current frost heave theory.

A comprehensive literature search on laboratory frost heave experiments was also performed. An inventory was made of laboratory frost heave experiments such as those of Penner, Konrad, Akagawa, and many others. A review framework was established that consists of a spreadsheet according to which procedures and results of individual tests could be categorized. Each frost heave experiment is described in terms of experiment details such as: column dimensions, boundary temperatures, freezing rates, temperature control, top down or bottom up freezing, ramped or step freezing, water intake rates and volumes, number of freeze-thaw cycles, and test duration and soil type. Innovations and shortcomings of the laboratory experiments are briefly addressed concluding with a description of the current state of frost heave testing, availability of data, experience, the value of laboratory tests for frost heave prediction, and as support for proposed frost heave theory and models.

A review framework was then established that consists of a spreadsheet according to which aspects of individual frost heave prediction models could be categorized and judged. This review framework is an amended version of the evaluation system described in Schellekens (1997). The aspects used for categorizing the proposed frost heave prediction models include the fundamental natural processes accounted for by each model, the manner that heat transfer, phase transfer, water flow, and resulting soil stress changes are accounted for, frost heave criteria, numerical and computing procedures used, assumptions and data requirements of each frost heave model. A comprehensive literature search on frost heave prediction models was performed. The review framework was used to describe the various aspects of a selection of the published models. Innovations and shortcomings of the models are briefly addressed concluding with a description of the current state of frost heave prediction modelling and our confidence level in the current frost heave models.

Finally, a literature search on the use of frost heave predictions for pipeline design was performed, to evaluate the requirements and procedures for reliable prediction of frost heave effects on chilled buried gas pipelines.

Literature searches included the publications and libraries of the Arctic Science and Technology Information System (ASTIS) of the University of Calgary, the Cold Regions Research and Engineering Laboratories (CRREL) of the US Army Corps of Engineers, and the Scott Polar Research Institute (SPRI) in Cambridge, UK, in addition to a library search at the University of Alberta and WWW-searches. The sources used for this paper are mainly from North America and Northern and Western Europe, with some publications in English by Russian, Chinese and Japanese researchers. The literature used is almost exclusively that, which exists in the public domain. It should be realized that many reports on frost heave around buried chilled gas pipelines are proprietary information of companies such as Canadian Arctic Gas Limited, Polar Gas, Foothills Pipe Lines Ltd., the Gas Arctic/Northwest Project Study Group or Northwest Alaskan Pipeline Company.

The assignment was concluded with a description of the present state of knowledge, the status of ongoing research, deficiencies and gaps in the knowledge base, and additional work required based on the reviews of frost heave theory, prediction models and performed tests.

## **2.0 FROST HEAVE THEORY**

### **2.1 Historical Review**

The theory to explain frost heave in soils has been developed and refined between 1920 and 1990. Frost heave has been studied by soil scientists, soil physicists, chemists, chemical engineers, geotechnical engineers, mathematicians, mechanical engineers, geographers, hydrologists and agricultural engineers. The development of frost heave theory, laboratory and field frost heave tests and frost heave prediction models, occurred in Canada, the USA, Russia, China, Japan, France, UK, Sweden, Norway and Finland. The findings have been published in in-house institutional reports, peer reviewed scientific journals, conferences and symposia.

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The scientists and practitioners usually published their findings in journals or presented at conferences and symposia of their own discipline. A lack of communication between practitioners from the various disciplines contributed to some misunderstanding and disagreement on the topic of frost heave between scientists and practitioners, until collaborations between scientists and practitioners from various disciplines started to generate useful results in the 1980's (e.g. Miller and O'Neill; and Guymon, Hromadka and Berg).

A number of useful state of the art papers on some aspects of frost heave have been presented by: Miller 1980, O'Neill 1983, Smith 1985, Nixon 1987, Kay and Perfect 1988, Ladanyi and Shen 1989, Black and Hardenberg 1991, Konrad 1994, Black 1995, Jones 1995, Kujala 1997 and Henry 2000. A summary of the most significant contributions to the development of the theory of frost heave is given in Table 1.

## 2.2 Current State

Frost heave is the upward movement of the ground surface or objects on or in the ground caused by the formation of ice in the soil. When a freezing front penetrates into a soil, its pore water freezes and expands, which is called in-situ freezing. Water from the unfrozen soil below is drawn into the freezing soil by a suction induced by the freezing process. This migrated water freezes in ice lenses that segregate the soil particles. This process is known as segregation freezing. Many thick ice lenses form in moist soils that have a hydraulic conductivity that is high enough for water flow to occur, and in which large water potential gradients develop during long periods of slow penetrating subzero temperatures. Such conditions occur in slow freezing of highly frost-susceptible fine-grained soils, in which the resulting segregated ice lenses account for most of the frost heave. An ice lens grows at some distance behind the freezing front (Andersland and Ladanyi 2004). The zone between the base of the warmest ice lens and a freezing front is known as the frozen fringe (Miller 1972). A new ice lens commences to form in the frozen fringe where the effective stress decreases to zero (normal stress equals neutral stress) or in other words where the ice pressure equals the cohesive and overburden pressures (Gilpin 1980). Water and ice in the frozen fringe may or may not be in thermodynamic equilibrium with each other regionally (or everywhere in the frozen fringe), though agreement exists that locally water and ice are in thermodynamic equilibrium.

**Table 1**  
**MOST SIGNIFICANT CONTRIBUTIONS TO FROST HEAVE THEORY**  
**DEVELOPMENT**

<b>Author(s)</b>	<b>Year</b>	<b>Contribution</b>
Bouyoucos	1920	Water in soil does not freeze at one temperature
Taber	1929	Frost heave is generated by growth of ice lenses instead of expansion of freezing water
Casagrande	1931	Frost heave susceptibility depends on the soil particle percentage finer than 20 $\mu\text{m}$
Beskow	1935	Frost heave can be limited by application of a surcharge on the soil surface
Schofield	1935	A pF scale for the Gibbs' free energy based on measured freezing point depression
Edlefsen and Anderson	1943	Rigorous analysis of the thermodynamics of soil moisture
Gold	1957	Frost heave mechanism based on the surface tension of the ice/water interface below the ice lens
Phillip and De Vries	1957	Water movement is a result of a thermal gradient
Jackson and Chalmers	1958	Heaving mechanism based on the kinetics of solidification
Cass and Miller	1959	The driving force of frost heave is the osmotic potential of diffuse electric double layers on grain surfaces.
Miller et al.	1960	The driving force of water flow to an ice lens is a combination of the osmotic potential gradient of diffuse electric double layers on grain surfaces and the surface tension of the water/ice interface below the ice lens.
Everett	1961	Rigorous analysis of the surface tension model implies an upper limit on the pressure at which an ice lens can grow.
Hoekstra	1966	Ice and water are not in equilibrium with each other during ice lens formation and frost heave.
Miller	1973	A capillary sink mechanism accounts for freezing induced moisture redistribution.
Groenevelt, Raats	1974 1975	Further theoretical development of heat and water transport in freezing soils using irreversible thermodynamics.
Miller et al.	1975	Further theoretical development of heat and water transport in freezing soils using irreversible thermodynamics, using commonly accepted soil functions.
Miller	1977	Ice forms in soils at the freezing front (primary heave) or behind the freezing front (secondary heave); ice in a frozen fringe beneath an ice lens moves by regelation at the same velocity as the ice lens.
Miller; Taylor and Luthin; Gilpin	1978 1980	Introduction of frost heave criteria for initiation of a new ice lens
Forland and Ratkje	1980	Further theoretical development of heat and water transport in freezing soils using irreversible thermodynamics.
Horiguchi	1987	The driving force of water flow to an ice lens is the osmotic potential gradient.
Shen and Ladanyi	1987	Introduction of a description of the stress field in freezing soil.

A soil in which a frost front penetrates experiences transient freezing. The frost heave resulting from the formation of each warmest ice lens and pore ice formation in the frozen fringe during this phase is known as transient frost heave (Konrad and Morgenstern 1982). Transient freezing is followed by stationary freezing, which occurs when the penetrating freezing front reaches a thermal equilibrium state, and will not further penetrate into the soil. During stationary freezing, only the frozen and partially frozen soil zones experience further cooling below 0° C. The frost heave associated with this stationary freezing phase occurs during the formation of the last ice lens, and is known as stationary frost heave (Akagawa 2000). Further freezing of unfrozen soil pore water and unfrozen water films surrounding soil particles behind the warmest ice lens or further growth of ice lenses behind the warmest ice lens due to water redistribution in the frozen soil, is known as long-term frost heave (Goto and Takahashi 1982). In summary, total frost heave consists of heave as a result of in situ freezing of pore water and growth of ice lenses, which both occur during transient, stationary and long term freezing.

Coarse-grained soils with relatively high gravel and coarse sand contents do not experience significant frost heave (Linnell and Kaplar 1959, Chamberlain 1981). In heavy clays, large water potential gradients are developed during freezing. However, their very low hydraulic conductivity limits the water flow to the freezing soil and with that, the amount of frost heave occurring. Soils with a high silt content are the most frost susceptible, due to relatively high suction compared to sands and relatively high hydraulic conductivity compared to clays.

Many soils in the Mackenzie Valley have an abundant water supply for frost heave. Under lakes, rivers and swamps the permafrost table is often lower than under the surrounding terrain, but the soil conditions under lakes, rivers and swamps are very wet. Frost heave may be limited due to low water availability in thick gravel and coarse sands, and in thick stiff, relatively dry clays, especially in regions with low precipitation (arid environments or so called polar deserts).

The osmotic potential gradient is an important part of the total water potential gradient that is the driving force of water movement from the unfrozen soil to the freezing soil zone. Soil pore water salts decreases the osmotic gradients and as a result, frost heave in soils with high soil pore water salinity is less than in soils with relatively low soil pore water salinity.

An increase in external surcharge on a soil limits the amount of frost heave of that soil. However, there is still debate about the existence or non-existence of a soil specific surcharge (or shut off pressure as mentioned by Arvidson and Morgenstern 1977, and Hill and Morgenstern 1977) that terminates frost heave completely.

### **3.0 SMALL SCALE LABORATORY FROST HEAVE EXPERIMENTS**

#### **3.1 Review Framework**

A frost heave laboratory experiment review framework was established that consists of a spreadsheet in which individual laboratory frost heave experiments could be compared to each other in terms of their purpose, procedures, methods, equipment and soils used, and in terms of their results.

#### **3.2 Historical Review**

Numerous laboratory and field experiments have been conducted to determine the frost heave potential of soils, to acquire input data for frost heave prediction models, and to validate frost heave theory and mathematical models. Most of the reviewed published test data were performed for a scientific purpose. Many frost heave tests performed for the design of foundations, pipelines, railways, road and airport pavements have not been published.

The number of published frost heave experiments increased from the mid 1950's up to 1990. An extensive (though far from complete) list of published frost heave tests is provided in Appendix A. The purpose, procedures, methods and equipment, soils, and the results of selected frost heave experiments are summarized in Table A.1 in Appendix A.

Typical laboratory frost heave tests involved temperature controlled freezing of an instrumented 1 to 30 cm (typically 10 cm) long soil column with a diameter of 6 to 30 cm (typically 10 cm) between a relatively cold and a relatively warm plate. The instrumentation consisted in most cases of 8 to 15 thermistors or thermocouples, a displacement (or frost heave) measuring device, and a water intake measuring device.

Pressure measuring devices such as small porous cups and internal strain measuring devices such as small lead spheres were included in some experiments. X-ray scans were taken to locate the lead spheres or to locate ice lenses during and after the frost heave experiment in some non-standard experiments.

Some experiments were performed in which a closed freezing system existed, i.e. the soil column did not have an external water supply, and did not experience a gain or loss of water. However, most tests were performed using open system freezing conditions, i.e. the soil column had an external water supply, and water could be taken up or could be discharged from the soil. Usually a constant head was maintained on the external source of water.

The experimental set up was placed in a temperature chamber to minimize heat loss and heat gains between the test soil and the surroundings. The temperature of each plate was usually controlled by circulating a fluid from a temperature controlled bath through the plate. Originally, top down freezing experiments were common, while bottom up freezing is applied in most current frost heave experiments, because the cold plate maintains a better contact with the soil during bottom up freezing than in a top down freezing experiment, and the side wall friction forces are reduced. Temperatures of the warm side of the column ranged from  $-0.2^{\circ}\text{C}$  to  $10^{\circ}\text{C}$  and temperatures of the cold side ranged from  $-20^{\circ}\text{C}$  to  $-0.1^{\circ}\text{C}$ . Originally ramped freezing experiments were performed in which the temperature of the cold plate and sometimes the warm plate were lowered at constant rates that ranged from  $-0.02$  to  $-10^{\circ}\text{C/hr}$ . Step freezing experiments in which the temperature of the cold side and sometimes the warm side of the soil column were lowered in 1 to 3 steps that ranged from  $-2$  to  $-15^{\circ}\text{C}$  have become more common over the last decades.

Most frost heave experiments have been performed with some surcharge or additional overburden on the soil column. This surcharge ranged from 20 to 250 kPa. In most experiments, the soil column was subjected to one freezing cycle, but in some experiments the soil column was subjected to one or more freezing and thawing cycles. The duration of a freezing cycle ranged from 2 to 1000 hrs, and the duration of a frost heave test ranged from 2 to 1000 hours, while the most common frost heave test duration was between 100 and 120 hours.

Prior to and after a frost heave experiment, soil properties such as particle size distribution, wet and dry density, porosity, moisture content and saturation were determined. The measured temperatures, total displacement or frost heave, and water intake were plotted vs. time. Pressures and displacements within the soil column were plotted vs. time in experiments in which these parameters were measured. Additional parameters such as thermal gradients, water intake rates and the segregation potential, were derived from these measurements.

Remoulded and undisturbed samples of a variety of soils ranging from clay and silts to granular soils such as sands and crushed limestone were used in frost heave tests. The most frequent tested soils were high frost susceptible clayey silts.

The most significant observations from frost heave experiments are listed in Table 2.

### **3.3 Current State**

Strict international or national standards for equipment, procedures and methods to perform frost heave tests, are currently not available despite occasional calls for such standards. A standard procedure was developed to perform frost heave tests at the National Research Council of Canada (Penner and Eldred 1985). Another frost heave test procedure, ASTM procedure (D5918-96) to determine the frost susceptibility of a soil was developed based on experimental work performed by Chamberlain et al. 1984 and Johnson et al 1986 at the United States Army Corps of Civil Engineers Cold Regions Research and Engineering Laboratories (CRREL) in Hanover, New Hampshire. This procedure is rarely used for tests to derive parameters for frost heave prediction.

Soil samples in most small scale or bench type frost heave tests in North America are frozen in a five day long open system bottom up freezing of remoulded or undisturbed soil samples that are typically 5 to 20 cm long and 6 to 15 cm in diameter in an instrumented frost heave cell. The instrumentation consists in most cases of 8 to 15 thermistors, a displacement (or frost heave) measuring device, and a water intake measuring device.

**Table 2**  
**SIGNIFICANT OBSERVATIONS FROM FROST HEAVE EXPERIMENTS**

Observations	Source
Rhythmic ice lens banding	Taber 1929, 1930, Martin 1959
Water migrates at sub-zero temperatures	Dirksen 1964, Hoekstra 1966
Heaving pressures are much higher than predicted by capillary driving force theory	Penner 1967, Hoekstra 1969 water movement paper, Sutherland and Gaskin 1973
Water flows through frozen soil	Hoekstra 1969, Xu at al. 1985
Hydraulic conductivity decreases with temperature below 0°C	Burt and Williams 1976
During initial rapid freezing water is expelled from the freezing soil into unfrozen soil	Penner and Ueda 1977, Loch and Kay 1978
Thermodynamic equilibrium exists at ice-water contact in frozen fringe	Vignes and Dijkema 1974, Biermans et al 1978
Frozen fringe exists	Loch and Kay 1978, Loch 1979
Water migrates within the frozen fringe	Penner and Walton 1978, Mageau and Morgenstern 1980
In one step frost heave tests the frost heave process occurs in three phases: 1. constant water intake velocity; 2. water intake velocity decreases continuously with time and 3. frost heave rate decreases monotonically with time (growth of final ice lens)	Konrad and Morgenstern 1980, Akagawa 1988
During formation of the last ice lens, the water intake is proportional to the temperature gradient	Konrad and Morgenstern 1980
Ice lenses can develop in frozen soil beyond the warmest ice lens	Penner and Goodrich 1980, Ohrai and Yamamoto 1985
Regelation occurs in freezing and frozen soil	Ohrai and Yamamoto 1985
Long term heave occurs	Caen experiment, Goto and Takahashi 1982
Transient frost heave accounts for 25% of the total frost heave, stationary heaving accounts for 70% and long-term heaving accounts for 5% of total frost heave in 400 hour long laboratory frost heave test	Caen experiment, Goto and Takahashi 1982

The warm side temperature is typically 0 to 5°C; the cold side temperature is typically -3 to -12°C, and the boundary temperature(s) are decreased in one to three temperature steps. The experimental setup is placed in a temperature chamber to minimize heat loss and heat gains between the test soil and the surroundings. The temperature of each plate is usually controlled by circulating a fluid from a temperature controlled bath through the plate. A constant head is maintained on the external source of water.

Most frost heave experiments are performed with some surcharge or additional overburden on the soil column. This surcharge ranges from 20 to 250 kPa, which is equivalent to 1 to 15 m of soil on top of the heaving soil sample. The soil column is typically subjected to one freezing cycle.

Prior to and after a frost heave experiment, soil properties such as particle size distribution, wet and dry density, porosity, moisture content and saturation are determined. The measured temperatures, total displacement or frost heave, and water intake are plotted vs. time. Additional parameters such as thermal gradients, water intake rates and the segregation potential, are derived from these measurements.

The following has been proven from frost heave tests:

- Ice forms in pores and in segregated ice lenses when a freezing front penetrates a soil containing water;
- The further the freezing front penetrates in the soil, the thicker the ice lenses and the further the lenses are spaced apart from each other;
- The ice lenses form in a direction perpendicular to the heat extraction, behind the freezing front;
- Water movement occurs from the unfrozen soil to the freezing soil as a result of a thermal gradient in a freezing soil;
- Slow freezing and associated small temperature gradients cause thicker ice lenses and more frost heave than fast freezing and associated large temperature gradients;
- Bottom up freezing of a soil column in a frost heave test results in a higher frost heave than that of a soil column subjected to top down freezing;
- Water movement occurs within the frozen fringe and within the frozen soil;
- Water redistribution during freezing occurs by water flow through unfrozen water films and movement of ice by regelation;

- Ice lenses continue to grow after new ice lenses have been formed at warmer locations within the soil;
- The water intake during the formation of the final ice lens in a laboratory frost heave test is proportional to the temperature gradient; the proportionality parameter is the segregation potential of the soil;
- The segregation potential is a function of the suction, thermal gradient and surcharge;
- Salt concentrations in the soil pore water decrease the amount of frost heave of the soil; and
- The amount of frost heave decreases with an increase in surcharge on the heaving soil.

The following is not proven, or requires further study:

- An extensive database of frost heave test results does not exist; and
- A method to (indirectly) measure pressure at the location where a new ice lens is forming, should be developed.

The following laboratories in Canada have frost heave test capabilities that have been used recently: AMEC Earth & Environmental Ltd., Calgary; Carleton University, Ottawa; EBA Engineering Consultants Ltd., Edmonton; Golder Associates, Calgary; and Laval University, Quebec City. C-Core in St. John's has the capability to perform centrifuge frost heave experiments.

## **4.0 FROST HEAVE PREDICTION MODELS**

### **4.1 Modelling of a Natural Process**

A natural process or system may be represented in a model, once knowledge of a process is obtained from experiments and observations in the field and laboratory. The more is known about the process involved, the better reality can be represented in the model. Models are used to predict the result of a process, and are used to develop a better understanding of the process.

The two main categories of models are: physical models (scale models and analog models) and theoretical models. A physical model may be used to visualize a problem.

An example of a scale model of the relief of the terrain is a 3D model made of gypsum or plastic. An example of an analog model is the representation of water flow by an electrical circuit. Theoretical models can be subdivided into: statistical models (random/phenomenological, probabilistic and stochastic models) and deterministic models (mechanistic or non-mechanistic models), or a mixture of these (e.g. stochastic-deterministic models). In a statistical model or process, probabilities or chances of a process happening, or a process variable taking a certain value, are calculated. The statistical model is called a random or phenomenological model, if the chances are based on correlation and not determined by any physical laws. The statistical model is called a probabilistic model, if the chances to get certain outcomes are larger than others. The probabilistic models are called stochastic models in the special cases that chances depend on time. In statistical models, the emphasis is on finding correlation between variables that might be important in the process, without knowing exactly how the process works. Therefore, these models are very useful in the exploratory phase of research into a process.

It may be possible to work towards a deterministic model when more details are known about the process. In a deterministic mode, the relation between cause and effect is mathematically described. A mechanistic model of a process in nature aims at a detailed physics-based description of all known sub-processes and interactions of variables involved in the process. Certain simplifying assumptions to omit complex or speculative relationships are used in a non-mechanistic model.

The process or system in reality may be represented or simulated by any of the models mentioned above. The most desirable description of reality is a mechanistic deterministic model. An exact solution of the problem may be obtained analytically, or an approximation of the exact solution may be found numerically once the problem is formulated mathematically in a mechanistic deterministic model. Sometimes numerical procedures lead to the exact solution. The main advantage of using numerical methods is that they can be written as a computer program, and a computer may perform the calculations.

A practical model is a model that delivers predictions that are as accurate as possible, while the model is kept simple or otherwise user friendly, computer requirements such as required software and hardware and required computing time are kept within reasonable limits, and for which the input parameters are relatively easy to determine.

Generalization, such as simplifying the physical base of the process by omitting certain details, or a decrease of the amount of spatial or temporal steps in the numerical approximation, may be necessary to reduce the computing time in order to make the model practical and to obtain an optimal efficiency. The errors generated by these actions should remain within a limited range. Whether these errors are allowable depends on the purpose of the model. Some degree of generalization or simplification, usually required to make scientific mechanistic deterministic models practical, results in non-mechanistic deterministic models being used in practice.

The input data required for the model should be evaluated. Input data which can be measured, and input data which cannot be measured should be estimated. Generalizations and approximations in the determination of the input data may be necessary and possible; however, the quality of the output of a model will only be as good as the quality of the model and its input data. It is important to know which parameters are crucial in the determination of the output. A sensitivity analysis can be performed to evaluate the sensitivity of the output to each of the input data parameters. The conditions under which the model is valid must be outlined. This depends on the assumptions and the validity of the physical laws used in the model.

The model has to be tested. Calculated results can be compared to measurements and observations of the calculated variables in reality (in natural processes those measurements may be field or laboratory measurements), or the calculated results may be compared with those calculated with other models. The latter method is less accurate than the former, because it is often not sure if the model with which the new model is compared is a close approximation of reality. The importance of each detail in a model can be evaluated by comparing a version of the model that incorporates that detail with a version that does not incorporate that particular detail.

## **4.2 Review Framework**

A review framework that consists of a spreadsheet in which various aspects of frost heave prediction models are listed has been developed to provide a means to describe and compare the models. These aspects include the fundamental natural processes accounted for by each model, the manner that heat transfer, phase transition, water flow, heat and water flow coupling and resulting soil stress changes are accounted for, and frost heave criteria. This review framework is an amended version of the frost heave model

evaluation system described by Schellekens (1997). A classification system is used to categorize the models, based on the natural processes model types mentioned in the previous section and the most significant features included in each model. The following categories of frost heave prediction models have been used:

1. Frost heave driving force models
  - a. Capillary driving force models
  - b. Adsorption driving force models
  
2. Frost heave prediction models
  - a. Statistical frost heave prediction models
  - b. Deterministic frost heave prediction models

Deterministic frost heave prediction models can be further categorized depending on whether they do include or do not include a frozen fringe (F), thermodynamic equilibrium (T), a frost heave criterion (C), regelation (R), and stress analysis (S). Assumptions determine if the deterministic model is mechanistic (M) or non-mechanistic (N). For example, the discrete ice lens model of Nixon (1991) is categorized as 2bFTCM.

### **4.3 Historical Review**

The first frost heave modelling attempts such as the work of Gold (1957), Cass and Miller (1959) and Everett (1961), focussed on the modelling of the driving force of water flow toward a freezing soil zone. The first frost heave prediction models that included a mathematical model of the frost heave process, numerical approximations of the analytical formulations, a computer code to perform the calculations, and an ultimate frost heave prediction were proposed in the 1970's. From the 1970's until the mid 1990's many models were proposed, while frost heave prediction modelling activity has decreased over the last decade. A listing of almost one hundred published frost heave models is given in Appendix B. A selection of the models listed was examined in detail using the review framework. The review is summarized in Table B.1 in Appendix B.

The most significant steps in the development of frost heave prediction modelling are listed in Table 3.

**Table 3**  
**MOST SIGNIFICANT DEVELOPMENTS IN FROST HEAVE PREDICTION**  
**MODELLING**

<b>Development</b>	<b>Source</b>
Model of the driving force of frost heave	Gold 1957
First frost heave prediction model using a coupled heat and water flow	Harlan 1973
First frost heave prediction model, a frost heave criterion and an ice phase moving by regelation	Miller 1978
Frost heave prediction model that used a slightly different frost heave criterion	Gilpin 1980
First detailed procedure to obtain frost heave prediction model input parameters and suggestions for their use in frost heave prediction	Konrad and Morgenstern 1980, 1981, 1982
First mechanistic solution of the Miller 1978 model	O'Neill and Miller 1982, 1985
First simplification (non-mechanistic solution) of O'Neill and Miller's 1982 solution of the Miller 1978 model	Holden and Jones 1985
A mechanistic model that considered the osmotic potential gradient as the driving force of frost heave	Horiguchi 1987
First frost heave prediction model that considered detailed stress development in the freezing soil	Shen and Ladanyi 1987
Redefinition of the mechanistic solution of the Miller 1978 model by O'Neill and Miller 1985, using the input parameter procedures proposed by Konrad and Morgenstern 1980, and addition of a detailed stress analysis	Shah 1990
Mechanistic frost heave prediction model that included solute transport	Padilla and Villeneuve 1990, 1992
Mechanistic two dimensional frost heave prediction model using a coupled heat and water flow, a frozen fringe, a frost heave criterion and stress analysis	Frémond and Mikkola 1991
Development of a practical standard frost heave prediction model by U.S. Army CRREL	Guymon et al. 1993
Development of a practical standard frost heave prediction model for frost heave prediction under Finnish roads	Saarelainen 1992
Development of a practical standard frost heave prediction model for frost heave prediction under Swedish roads	Sheng et al. 1995
Further simplification of the O'Neill and Miller's 1982 solution of the Miller 1978 model	Fowler and Noon 1993, Gorelik et al. 1998, Fowler 2003

#### 4.4 Current State

The current practical frost heave prediction models are non-mechanistic deterministic models, in which the soil subjected to freezing is divided into three zones: the frozen zone, the frozen fringe and the unfrozen zone. Water and heat flow, and deformations as a result of stresses and pressures, are treated separately for each zone. The frozen fringe is a very thin zone with a thickness depending on soil type and freezing rate, varying mainly from a fraction of 1 mm to 10 mm, and up to 100 mm where very small thermal gradients exist. The latent heat release in this thin zone originally generated many computational problems. Continuum mechanics procedures gained popularity since the early 90's. In these procedures, the frozen fringe is reduced to a boundary over which parameters jump in value. This treatment has had considerable success.

Heat transfer and phase transition in each zone of the freezing soil are described by the Fourier equation and mass energy continuity equation, often combined in the general heat transfer equation. Current frost heave prediction models consider a water potential gradient induced by the thermal gradient in a freezing soil as the driving force for water flow from the unfrozen soil to the freezing soil. The Darcy and mass continuity equations, often combined in the general moisture transfer equation, are used to describe water flow in the unfrozen zone, frozen fringe and frozen zone. The heat and water transfer are coupled in a form of the Clausius-Clapeyron equation, which is valid for thermodynamic equilibrium in the frozen fringe, especially at the base of the ice lens.

In the frost heave prediction model, a relationship or frost heave criterion is included that prescribes the location of the formation of the new (warmest) ice lens. Examples of such a criterion are: 85% ice content in soil pores (Taylor and Luthin 1978), zero effective stress (Miller 1978), or a separation pressure equalling overburden pressure and cohesion (Gilpin 1980). Some models include a detailed stress analysis, describing elastic and viscous behaviour using Hooke's law and either the Prandtl-Reuss or Norton-Hoff law. The frost heave calculation includes freezing of pore water in situ and freezing of water in segregated ice lenses.

The analytical formulation of the coupled heat and water flow equations is usually approximated by a Galerkin weighted residual finite element method in the space domain and a finite difference method in the temporal domain. The analytical formulation of the

stress analysis is usually approximated by a Ritz finite element method in the space domain and a finite difference method in the temporal domain.

Published frost heave prediction models currently used in practise are given with the regions in which they are used in Table 4:

**Table 4**  
**PUBLISHED FROST HEAVE PREDICTION MODELS CURRENTLY USED**

<b>Model Developer</b>	<b>Institute or Company</b>	<b>Region of Use</b>
Nixon 1991	Nixon Geotech	Canada, Alaska
Konrad and Morgenstern 1980	Laval University	Canada, Japan
Guymon et al. 1993	Cold Regions Research & Engineering Laboratory (CRREL)	USA
N/A	Transport and Road Research Laboratory (TRRL), Department of the Environment	UK
Frémond and Mikkola 1991, 1993	Laboratoire Central des Ponts et Chaussées (LCPC)	France
Sheng et al 1995	University of Technology Lulea	Sweden
Saarelainen 1992 (SSR)	Valtion Teknillinen Tutkimuskeskus (VTT, Technical Research Centre)	Finland

Successful predictions have been claimed by the authors of all the models mentioned in Table 4.

Description of the heat flow requires knowledge about the thermal properties of the soil, and the local cyclical climatic input data, including climatic trends. Darcy flow through the frozen fringe requires the hydraulic conductivity of the frozen fringe. This hydraulic conductivity of the frozen fringe is the most significant input parameter required in frost heave prediction models because it varies with temperature below 0°C by several orders of magnitude. Nixon (1991) presents a compilation of measured subzero hydraulic conductivities. Konrad and Morgenstern (1980, 1981) proposed a water flow to the warmest ice lens determination method that avoids determination of the hydraulic conductivity of the freezing fringe. This method uses the temperature gradient and a mapped soil specific segregation potential surface, and has been successfully applied in

many engineering design projects. Nixon's compilation could be extended and used concurrently with Konrad and Morgenstern's SP-method to determine the water flux density in the frozen fringe.

Other frost heave prediction model input parameters that are difficult to determine are the frost heave criteria such as the stress partitioning factor of Miller 1978 or the separation pressure of Gilpin 1980, although some researchers and practitioners who developed solutions of these two conceptual models claimed good agreement of predicted and measured frost heave in laboratory experiments after estimating these parameters.

A few researchers continue with efforts to improve existing frost heave models (e.g. a version of the Miller 1978 model by Fowler 2003), although currently not much effort is put towards the further development of the existing frost heave models. A 3-dimensional frost heave prediction model has not been published.

The frost heave prediction models that show the most promise for further development are those of Shen and Ladanyi (1987), Frémond and Mikkola (1991), and Shah (1990). Advances have been made to simplify and improve Frémond and Mikkola's model. Shah's model could be simplified. A first attempt of simplification by Wang (1994) was not successful, because critical elements such as the frost heave criterion were omitted. Currently most of the modelling effort focuses on the development of frost heave models for four specific applied purposes:

- Modelling of (differential) frost heave along buried chilled gas pipelines;
- Modelling of (differential) frost heave along (oil) pipelines in cold environments;
- Modelling of (differential) frost heave under highway and airport pavements and railroad tracks; and
- Modelling of (differential) frost heave under and around foundations, piles and retaining walls

These four fields of frost heave prediction application have their own specific issues. The first category of frost heave models is further discussed in the following section.

## **5.0 FROST HEAVE PREDICTION FOR BURIED CHILLED GAS PIPELINES**

### **5.1 Problem Statement**

The prediction of frost heave around buried chilled gas pipelines requires the following to be considered:

- a frost heave prediction model as presented in Section 4.4;
- the complex geometry due to a planar heat source or heat sink at the soil surface, and a cylindrical heat source or heat sink formed by the pipeline;
- the seasonal variability of the ground surface thermal boundary;
- the response of the pipeline to the frost heave process; and
- the soil-pipeline interaction.

Buried chilled gas pipelines generate freezing and frost heave of the surrounding soil in addition to the natural occurring freezing and frost heave. In the summer, the soil surrounding the chilled gas pipeline is warmer than the pipeline. Heat flow occurs from the soil surface downward, and from the soil surrounding the pipeline towards the pipe. The pipeline itself is the source of cooling, freezing and frost heave. In the winter the soil surrounding the pipeline is colder than the pipeline and heat flows from the pipeline towards the surrounding soil. A 2-D or 3-D frost heave prediction model is required for a proper modelling of soil freezing and frost heave around a buried chilled gas pipeline.

### **5.2 Historical Review**

Frost heave prediction models for buried chilled gas pipelines in North America have been developed since northern gas pipelines were proposed in the early 1970's. The number of publications and the advances in this field of study have increased substantially over the last 15 years, however, a state of the art review of frost heave prediction for buried gas pipelines does not exist. A listing of publications on frost heave prediction models for buried gas pipelines is presented in Appendix C. A selection of publications was examined and is summarized in Table C.1 in Appendix C. A summary of the most significant steps in the development of frost heave prediction modelling for buried chilled gas pipelines is presented in Table 5.

**Table 5**  
**SIGNIFICANT DEVELOPMENTS IN FROST HEAVE PREDICTION FOR**  
**BURIED CHILLED GAS PIPELINES**

<b>Author</b>	<b>Year</b>	<b>Development</b>
Hwang	1977	Model predicting upper-bound frost heave under buried chilled gas pipeline (model includes capillary suction, shut-off pressure, and does not include frozen fringe and detailed stress analysis).
Several authors	Up to 1980	Soil response to frost heave is represented as discrete 1D spring or Winkler elements.
Sharma and Pralong	1982	Improved Stefan/Neumann approach to soil freezing using internal energy, enthalpy and heat flux; no water flow, ice lens formation or stress considerations.
Nixon et al.	1983	Soil mass is treated as an elastic or viscous continuum. Solution using STARDYNE stress analysis package and HERMAN non-linear finite element stress analysis program. Heave computed using SP.
Konrad and Morgenstern	1984	Calculation of thermal field around the pipeline using cylindrical polar coordinate system; incremental total frost heave calculation, using SP to calculate water flow density in frozen fringe.
Shen and Ladanyi	1987	2D hydrodynamic frost heave prediction model with detailed stress analysis, frost heave criterion of Taylor and Luthin 1978.
Fremond and Mikkola	1991	Use of continuum mechanics to model frost heave around a buried chilled gas pipeline.
Selvadurai	1992	Description of the 6 required elements of frost heave prediction around chilled buried gas pipelines.
Nixon	1992	Discrete ice lens model; use of quasi static 2D method of Hwang to determine temperature gradients beneath buried pipeline; use of these gradients in the discrete ice lens model; no detailed soil and pipeline stress analysis.
Shah and Razaqpur	1993	2D rigid ice model predicting frost heave around pipelines using Galerkin finite element solution method in space.
Selvadurai et al.	1999	3D hydrodynamic frost heave prediction model based on Shen and Ladanyi 1987, includes stress analysis and frost heave criterion of Taylor and Luthin 1978. Achieved better agreement with measured data than Shen and Ladanyi 1987.

Comprehensive analysis of a soil-pipeline interaction problem that describes soil freezing and frost heave around a buried chilled gas pipeline should take into account:

1. Coupled heat flow and moisture transport within the frozen and unfrozen soils;
2. The mechanical behaviour of the unfrozen soil in particular the soil response to freezing and frost heave;
3. Moving boundary problems associated with a moving freezing front and frost heave;
4. Growth of pore ice and ice lenses;
5. Mechanical behaviour of the buried pipeline, which includes the structural response of the pipeline; and
6. Interface conditions at the soil-pipeline interface

The models used for frost heave prediction around buried chilled gas pipelines have become more sophisticated with time. The modelling efforts commenced with very elementary Stefan/Neumann approaches, followed by elementary SP application, and eventually to a 2D rigid ice model and a 3D form of the Shen and Ladanyi (1987) model.

Similar trends are observed for the modelling of the response of the soil to heaving. Originally the soil was represented as a discrete 1D spring or Winkler element, and later as a 2D or 3D continuum which included viscous and elastic behaviour. Plastic behaviour of the frozen soil as a result of pipeline uplift has also been modelled.

Shen and Ladanyi (1989) and others have considered the moving boundary problems and optimizing numerical efficiencies required for pipeline problems in freezing ground. Mechanical behaviour of the pipeline has been modelled simply as a flexible beam which possesses flexural, axial shear and torsional stiffness, and more complex as a cylindrical shell which can possess complex non-linear stress-strain-time phenomena. The gas pressure in a pipeline decreases with distance from the last compressor and chilling station. The gas temperature decreases with the pressure decrease, according to the Joule-Thompson effect, and the pipeline temperature reaches a minimum when the gas arrives at a compressor station, where it is subsequently chilled and compressed. The pipeline temperature decrease with distance from a compressor station has to be taken into account in frost heave modelling for buried chilled gas pipelines.

Interface behaviour of the soil and the pipeline has been simply described by either continuity or separation in the displacements between the pipeline and the one dimensional soil models. This interface behaviour can be described by interface phenomena such as frictionless contact, frictional contact or bonded contact and interface constitutive models determined from experiments, although presently it has almost exclusively been described by bonded contact.

### **5.3 Current State**

The state of the art of the modelling of the six elements of the frost heave prediction around buried chilled pipelines is described below.

1. Coupled heat flow and moisture transport within the frozen and unfrozen soils is addressed in Section 4.4.
2. The mechanical behaviour of the unfrozen soil, in particular, the soils response to the freezing soil is modelled as a 2D or 3D continuum.
3. A finite element discretization is used which accommodates the complex coupled heat and water flows and displacements that accompany the between horizontal and pipeline concentric pattern of ice lens growth.
4. Growth of pore ice and ice lenses is addressed in Section 4.4.
5. The buried pipeline is represented as a cylindrical shell which can possess complex non-linear stress-strain-time phenomena.
6. The soil - pipeline interface behaviour is described by interface phenomena such as frictionless contact, frictional contact or bonded contact and interface constitutive models.

The manner in which the models are applied varies from simple to complex. The most simple application of frost heave prediction around buried chilled pipelines is a repetition of the application of a simple one dimensional frost heave prediction model along the pipeline using the location specific thermal regime and soil properties. The frost heave under the pipeline is predicted, which is used to calculate the resulting stress in the pipeline.

The most complex application of frost heave prediction around buried chilled pipelines uses a two or three dimensional frost heave prediction model along the pipeline using location specific thermal and hydraulic soil properties defined at nodes of a mesh around

the pipeline. Frost heave effects including the strains at every node around the pipeline are predicted, and the calculated strains around the pipeline are used to calculate the resulting stress in the pipeline. The response of the soil to pipeline uplift is also predicted.

#### 5.4 Input Data for Models Predicting Frost Heave Around Buried Chilled Gas Pipelines

Table 6 provides the input data required for the prediction of frost heave around buried chilled gas pipelines, and the source of these input data:

**Table 6**  
**INPUT DATA AND DATA SOURCES REQUIRED FOR FROST HEAVE**  
**PREDICTION AROUND BURIED CHILLED GAS PIPELINES**

<b>Data</b>	<b>Source</b>
Climatic data (temperature, precipitation, snow cover thickness)	Weather stations
Soil properties (e.g. soil moisture content, particle size distribution, Atterberg limits, salinity and organic content)	Site investigations along proposed pipeline route; laboratory index testing; ditch wall logging, geophysical programs
Thermal soil conditions	Instrumentation, geophysical program
Segregation potential	Small scale laboratory frost heave tests
Hydraulic conductivity	Small scale laboratory frost heave tests
Unfrozen water contents	Laboratory TDR tests

#### 6.0 STATUS OF ONGOING RESEARCH

Most of the ongoing frost heave research is currently focused on application of frost heave prediction for specific applications such as buried gas chilled pipelines, road and airport pavements, and building foundations. Experimental frost heave research has decreased from the high research intensity in the 1970's and 1980's, especially in North America, over the last decade. Further development of frost heave prediction models still occurs in the UK, Sweden, Finland, China and Russia.

Centres where researchers or practitioners have worked on some aspects of frost heave theory, testing and/or modelling are listed in Appendix D. Frost heave research is ongoing at institutions and companies listed in Table 7.

**Table 7**  
**INSTITUTIONS AND COMPANIES WITH ON-GOING**  
**FROST HEAVE RESEARCH**

<b>Institution or Company</b>	<b>City</b>	<b>Country</b>
Carleton University	Ottawa	Canada
Laval University	Laval	Canada
C-Core	St.John's	Canada
Nixon Geotech	Calgary	Canada
McGill University	Montreal	Canada
CRREL	Hanover	USA
University of Alaska	Fairbanks	USA
Northern Engineering & Scientific	Anchorage	USA
Exxon Production Research Company	Houston	USA
University of Colorado	Boulder	USA
University of Nottingham, British Drilling & Freezing Co.	Nottingham	UK
Oxford University	Oxford	UK
University of Aston	Birmingham	UK
LCPC	Paris	France
Technical University of Lulea	Lulea	Sweden
VTT	Espoo	Finland
Helsinki University of Technology	Helsinki	Finland
University of Oulu	Oulu	Finland
Moscow State University	Moscow	Russia
Earth Cryosphere Institute SB RAS	Tyumen	Russia
Hokkaido University	Sapporo	Japan
Lanzhou Institute of Glaciology and cryopedology	Lanzhou	China

A more accurate account of current and past activity on frost heave theory, testing and modelling can be obtained by mailing a questionnaire to the centres listed in Appendix D.

## **7.0 FROST HEAVE EVALUATION SUMMARY**

The number of publications on frost heave has increased considerably since the Berger inquiry in the 1970's. Frost heave theory developed by Miller 1978 has been proven in laboratory experiments and is accepted widely. A procedure proposed by Konrad and Morgenstern 1980 to characterize frost susceptible soil in small scale laboratory tests in terms of their segregation potential is used in many applications. The rapid freezing, associated large thermal gradients, short test duration, and limited sample size have been recognized as limitations of small scale laboratory frost heave tests. Large scale

laboratory and field frost heave tests have been used to evaluate scale effects. In addition, scaled frost heave tests in centrifuges have dealt with some of the testing time constraints.

All current frost heave prediction models describe a set of variations of the same equations such as Fourier's law, the heat continuity law, Darcy's law, the mass continuity law, the Clausius-Clapeyron equation, and include a frost heave criterion for the frozen zone the frozen fringe and the unfrozen zone of the freezing soil profile. The models that include a stress analysis describe elastic and viscous behaviour by Hooke's law and either the Norton-Hoff or Prandtl-Reuss law respectively. Most researchers and practitioners who proposed frost heave prediction models claimed successful and accurate predictions, validated by tests. Models that have been applied for frost heave prediction are provided in Table 4.

Research efforts in frost heave prediction for buried chilled pipelines have increased since 1980. This research has benefited from large scale laboratory and field test programs such as the experiments in Fairbanks, Calgary and Caen. Computed pipe stresses caused by differential heave at a sand-silt boundary in the Caen experiment give a good indication of the maximum differential stresses that can be expected in the pipeline. Validation of the frost heave predictions around the buried pipelines in these large scale facilities is beyond the scope of this paper.

Accurate frost heave prediction is considered to be in an advanced research state. Presently, frost heave predictions are not routinely carried out in industry and commercial software is not available. However, conservative estimates of frost heave upper bounds enable a safe design of chilled gas pipelines. The current trend in modelling for frost heave design of chilled pipelines is to make these upper bound estimates less conservative.

The most difficult aspect of frost heave prediction is the acquisition of the input data for frost heave prediction models. Frost heave prediction for a buried chilled gas pipeline adds another degree of complexity as the soil properties along the pipeline can vary significantly. It is not possible to characterize soil properties along an entire pipeline. A sensitivity or probability approach must be carried out to evaluate the influence of soil properties on the frost heave prediction. The spatial variability of the soil properties along the pipeline routing must be assessed. Conservatism must be used in the pipeline

design to accommodate for uncertainties in and variability of the input parameters in the frost heave prediction model, and for generalizations in the prediction model itself.

Most frost heave predictions resulted in over-prediction of long-term frost heave (e.g. Konrad and Morgenstern 1984, Shen and Ladanyi 1987, and Nixon 1991), and representation of the soil by Winkler elements over-predicts the pipeline stresses generated by the maximum differential frost heave. Therefore, the simpler and older methods that predict differential frost heave around buried chilled gas pipelines provide conservative upper-bound estimates of frost heave and frost heave generated pipeline stresses, required for safe pipeline design.

## **8.0 FURTHER REVIEW AND RECOMMENDATIONS**

Frost heave knowledge could benefit from the following research activities:

- A thorough elementary examination of the driving force of frost heave;
- Development of a method to measure the hydraulic conductivity in the frozen fringe;
- Development of an extensive database of frost heave test results;
- Standardization of frost heave test procedures and equipment;
- Development of a method to indirectly measure pressure at the location where a new ice lens forms;
- A three dimensional frost heave prediction model based on Miller's rigid ice model, Shen and Ladanyi's model or Nixon's discrete ice lens theory, including an extensive stress analysis such as given by Shen and Ladanyi;
- Commercial development of such an advanced practical model;
- Clearer statements of the input parameters required for each frost heave prediction model. Access to the computer code is often required to list these input parameters; and
- An overview of frost heave prediction for buried chilled gas pipelines that includes discussion of pipeline mechanics.

The research activities suggested above are not necessary requirements for safe pipeline design, but merely of academic, clarifying and informative value.

Design of a chilled buried gas pipeline must consider the following:

- An upper-bound estimate of the differential movement and stresses imposed on a pipeline due to frost heave and other processes;
- An assessment of the level of accuracy in frost heave prediction required to safely construct and operate a buried chilled gas pipeline;
- A thorough review of (differential) frost heave effects mitigation measures;
- A thorough review of pipeline materials and their ability to withstand stresses generated by differential frost heave;
- An evaluation of pipeline construction techniques that can limit differential frost heave stresses; and
- An extensive monitoring program during pipeline operation.

The quality of frost heave prediction models for buried chilled gas pipelines can only be fully assessed based on their performance and accuracy in predicting the stress-strain behaviour of soil and pipelines in large scale laboratory and field experiments. It is understood that the GSC has commissioned another report to review this aspect.

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## 9.0 CLOSURE

EBA is pleased to have provided this state of the art paper on frost heave. Please do not hesitate to contact the undersigned should you have any questions or comments regarding this paper.

Yours truly,  
EBA Engineering Consultants Ltd.



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**APPENDIX A**

**SMALL SCALE FROST HEAVE EXPERIMENTS  
LISTING AND COMPARISON**

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**FROST HEAVE EXPERIMENTS REFERENCE LIST**  
(the publications printed in bold are summarized in Table A.1)

- A1. **Akagawa, S., 1988a. Evaluation of the X-ray radiography efficiency for heaving and consolidation observation. Ground Freezing 88, Fifth International Symposium on Ground Freezing, Nottingham, R.H. Jones and J.T. Holden eds., A.A. Balkema, Rotterdam, pp. 23-28.**
- A2. **Akagawa, S., 1988b. Experimental study of frozen fringe characteristics. Cold Regions Science and Technology, Vol. 15, pp. 209-223.**
- A3. **Akagawa, S., 2000. A method for controlling stationary frost heaving. Ground Freezing 2000 – Frost Action in Soils, Ninth International Symposium on Ground Freezing, Leuven, J.F. Thimus ed., A.A. Balkema, Rotterdam, pp. 63-68.**
- A4. **Akagawa, S., and Fukuda, M., 1991. Frost heave mechanism in welded tuff. Permafrost and Periglacial Processes, Vol. 2, pp. 301-309.**
- A5. **Akagawa, S., Yamamoto, Y., and Hashimoto, S., 1985. Frost heave characteristics and scale effect of stationary frost heave. Ground Freezing 85, Fourth International Symposium on Ground Freezing, Sapporo, S. Kinoshita and M. Fukuda eds., A.A. Balkema, Rotterdam, pp. 37-143.**
- A6. **ASTM Designation D5918-96. Standard Test Methods for Frost Heave and Thaw Weakening Susceptibility of Soils, pp. 795-804.**
- A7. Berg, R.L., Ingersoll, J., and Guymon, G.L., 1980. Frost heave in an instrumented soil column. Cold Regions Science and Technology, Vol.3, pp. 211-221.
- A8. Goto, S., and Takahashi, Y., 1982. Frost heave characteristics of soil under extremely low frost penetration rate. Proceedings of the Third International Symposium on Ground Freezing, Hanover, NH, US Army Corps of Engineers, pp. 261-268.
- A9. **Hazen, B., Nixon, J.F., Heuer, C.E., Caldwell, J.B., and Brudie, E.L., 1993. Frost heave predictions for Alaskan soils. Permafrost, Sixth International Conference, Proceedings, Beijing, J. Brown, H.M. French, N.A. Grave, G. Cheng, L. King, and E.A. Koster eds., South China University of Technology Press, Wuhan, pp. 244-249.**
- A10. Hoekstra, P., 1969. Water movement and freezing pressures. Soil Science Society of America Proceedings, Vol. 33, n. 4, pp. 512-518.

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- A11. **Ishizaki, T., and Nishio, N., 1988. Experimental study of frost heaving of a saturated soil. Ground Freezing 88, Fifth International Symposium on Ground Freezing, Nottingham, R.H. Jones and J.T. Holden eds., A.A. Balkema, Rotterdam, pp. 65-72.**
- A12. **Ito, Y., Vinson, T.S., Nixon, J.F., and Stewart D., 1998. An improved step freezing test to determine segregation potential. Permafrost, Seventh International Conference, Proceedings, Yellowknife, Lewkowicz and Allard eds., Collection Nordicana No.57, Université Laval, Laval, pp. 509-516.**
- A13. Jessberger, H.L., and Jagow, R., 1989. Determination of frost susceptibility of soils. Frost in Geotechnical Engineering, International Symposium Saariselkä, VTT symposium 95, H. Rathmayer ed., Technical Research Centre of Finland, Espoo, Vol.2, pp. 449-469.
- A14. Knutsson, S., Domaschuk, L., and Chandler, N., 1985. Analysis of large scale laboratory and in situ frost heave tests. Ground Freezing 85, Fourth International Symposium on Ground Freezing, Sapporo, S. Kinoshita and M. Fukuda eds., A.A. Balkema, Rotterdam, pp. 65-70.
- A15. **Konrad, J.M., 1987. Procedure for determining the segregation potential of freezing soils. Geotechnical Testing Journal, Vol. 10, No.2, pp. 51-58.**
- A16. Konrad, J.M., 1989. Pore water pressure at an ice lens: its measurement and interpretation. Cold Regions Science and Technology, Vol. 16, pp. 63-74.
- A17. Konrad, J.M., and Nixon, J.F., 1994. Frost heave characteristics of a clayey silt subjected to small temperature gradients. Cold Regions Science and Technology, Vol.22, pp. 299-310.
- A18. Kujala, K., and Ravaska, O., 1989. Influence of test conditions and equipment on the frost heave test. Frost in Geotechnical Engineering, International Symposium Saariselkä, VTT symposium 95, H. Rathmayer ed., Technical Research Centre of Finland, Espoo, Vol.2, pp. 931-944.
- A19. McGaw, R., 1972. Frost heaving versus depth to water table. Highway Research Record, Vol. 393, pp. 45-55.
- A20. **Nakano, Y., and Horiguchi, K., 1985. Role of phase equilibrium in frost heave of fine grained soil under negligible overburden pressure. Advances in Water Resources, Vol. 8, pp. 50-68.**

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- A21. Nishimura, T., Ogawa, S., and Fukuda, M., 1994. Effective stress in unsaturated soils after freezing and thawing. *Ground Freezing 94, Seventh International Symposium on Ground Freezing*, Nancy, M. Frémond ed., A.A. Balkema, Rotterdam, Vol.1, pp. 121-128.
- A22. Nixon, J.F., 1982. Field frost heave predictions using the segregation potential concept. *Canadian Geotechnical Journal*, Vol. 19, pp. 526-529.
- A23. Ohrai, T. and Yamamoto, H., 1985. Growth and migration of ice lenses in partially frozen soil. *Ground Freezing 85, Fourth International Symposium on Ground Freezing*, Sapporo, S. Kinoshita and M. Fukuda eds., A.A. Balkema, Rotterdam, pp. 79-84.
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- A25. Penner, E., 1986. Aspects of ice lens growth in soils. *Cold Regions Science and Technology*, Vol. 13, pp. 91-100.
- A26. Penner, E., and Eldred, D., 1985. Equipment and methods for soil frost action studies. National Research Council of Canada, Division of Building Research, DBR Internal Report No. 503, 8 p.**
- A27. Penner, E., and Goodrich, L.E., 1980. Location of segregated ice in frost susceptible soil. *Second International Symposium on Ground Freezing*, Trondheim, P.E Frivik, N. Janbu, R. Saetersdal and L.I. Finborud eds., Norwegian Institute of Technology, pp. 626-639.
- A28. Penner, E., and Ueda, T., 1978. A soil frost-susceptibility test and a basis for interpreting heaving rates. *Permafrost, Third International Conference, Proceedings*, Edmonton, National Research Council of Canada, Ottawa, Vol. 1, pp. 721-727.
- A29. Penner, E., and Walton, T., 1979. Effects of temperature and pressure on frost heaving. *Engineering Geology*, Vol. 13, pp. 29-39.
- A30. Radd, F.J., and Oertle, D.H., 1973. Experimental pressure studies of frost heave mechanisms and the growth-fusion behaviour of ice. *Permafrost, Second International Conference, Proceedings*, Yakutsk, Vol. 1 North American contribution, National Academy of Sciences, Washington DC, pp. 377-384.
- A31. Ryokai, K., 1985. Frost heave theory of saturated soil coupling water/heat flow and its application. *Ground Freezing 85, Fourth International Symposium on Ground Freezing*, Sapporo, S. Kinoshita and M. Fukuda eds., A.A. Balkema, Rotterdam, pp. 101-108.

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- A32. Seto, J.T.C., and Konrad, J.M., 1994. Pore pressure measurements during freezing of an over consolidated clayey silt. *Cold Regions Science and Technology*, Vol. 22, pp. 319-338.
- A33. Sheng, D., Axelsson, K., and Knutsson, S., 1995. Estimation of frost heave for stratified soil profile. *Ground Freezing 94, Seventh International Symposium on Ground Freezing*, Nancy M. Fremont ed., A.A. Balkema, Rotterdam, pp. 129-142.
- A34. Sheng, Y., 1994. Calculation of frost heave in saturated soil under constant surcharge. *Seventh International Cold Regions Engineering Specialty Conference*, Edmonton, ASCE/CSCE, pp. 729-735.
- A35. Sutherland, H.B., and Gaskin, P.N., 1973. Pore water and heaving pressures developed in partially frozen soils. *Permafrost, Second International Conference, Proceedings*, Yakutsk, USSR. North American Contribution, pp. 409-419.
- A36. Svec, O.J., 1981. Frost heave control of a chilled gas pipeline. *Cold Regions Science and Technology*, Vol. 4, pp. 215-225.
- A37. Svec, O.J., 1989. A new concept of frost heave characteristics of soils. *Cold Regions Science and Technology*, Vol. 16, pp. 271-279.
- A38. Takashi, T., Ohrai, T., Yamamoto, H., and Okamoto, J., 1980. Upper limit of heaving pressure derived by pore water pressure measurements of partially frozen soil. *The Second International Symposium on Ground Freezing*, Trondheim, Norwegian Institute of Technology, pp. 713-724.
- A39. Takeda, K., 1988. Experimental study on ice segregation during soil freezing. Thesis, Hokkaido University, Sapporo, Japan, 78 p.
- A40. Takeda, K., and Nakano, Y., 1990. Quasi-steady problems in freezing soils: II Experiment on the steady growth of an ice layer. *Cold Regions Science and Technology*, Vol. 18, pp. 225-247.
- A41. Williams, P.J., Riseborough, D.W., and Smith, M.W., 1992. The France-Canada joint study of deformation of an experimental pipeline by differential frost heave. *Proceedings of the Second International Off-shore and Polar Engineering Conference*, San Francisco, ISOPE, Vol. II, pp. 40-45.
- A42. Williams, P.J., and Wood, J.A., 1985. Internal stresses in frozen ground. *Canadian Geotechnical Journal*, Vol. 22, pp. 413-416.

- A43. Wood, J.A., and Williams, P.J., 1985. Stress distribution in soils. Ground Freezing 85, Fourth International Symposium on Ground Freezing, Sapporo, S. Kinosita and M. Fukuda eds., A.A. Balkema, Rotterdam, pp. 165-171.
- A44. Yanagisawa, E., and Yao, Y.L., 1985. Moisture movement in freezing soils under constant temperature condition. Ground Freezing 85, Fourth International Symposium on Ground Freezing, Sapporo, S. Kinosita and M. Fukuda eds., A.A. Balkema, Rotterdam, pp. 85-91.

TABLE A.1 SMALL SCALE FROST HEAVE EXPERIMENTS COMPARISON (PAGE 1 OF 3)

Frost heave experiments reference nr. author(s)	A1 Akagawa 1988a	A2 Akagawa 1988b	A3 Akagawa 2000	A4 Akagawa and Fukuda 1991
purpose	strain distribution profiles	strain distribution profiles		to show frost heave in turf
length of column (m)	0.095	0.097	0.06	0.25 and 0.15
diameter of column (m)	0.06	0.06	0.06	0.29 and 0.05
number of layers	?	?		
dry density (kg/m <sup>3</sup> )	1450	1450		
water content				0.3
porosity				92, 100
saturation (%)				
temperature top (oC)	warm: 2.2 and 3.0	warm: 3.0	warm: 0.2	cold: -14 and -5
number of temperature sensors	15	15		10
temperature bottom (°C)	cold: -5.9 and -5.5	cold: -5.5	cold: -5.5	warm: 4.5 and 2
open system	yes	yes	yes	yes
closed system	no	no	no	no
initializing ice nucleation	no	no	no	no
ramped freezing	N/A	N/A	N/A	N/A
ramp rate (°C/hr)	1 step	1 step	1 step	1 step
temperature step (°C)	?	?	?	?
duration step (hr)	yes	yes	yes	yes
temperature control bath (°C)	?	0	0	yes
temperature control chamber (°C)	?	0	0	yes
freeze-thaw cycles	1 freezing	1 freezing	1 freezing	1 freezing
test duration (hr)	1000 and 650	700	450	1000 and 250
water supply	yes	yes	yes	yes
constant head	yes	yes	yes, 0 kPa	yes
pore water pressure measurement	no	no		during second series at 0.03, 0.05 and 0.07 m from top just to maintain contact
surcharge (kPa)	60 and 110	110	60	yes
displacement measurement	yes	yes	yes	yes
SP vs. time (K and M or Nixon method)			no, but possible	
temperature profile at time t	yes	yes	yes	
frost heave vs. time	yes	yes	yes	
frost penetration vs. time	yes	yes	yes	
water intake vs. time	yes	yes	yes	
final water content profile		yes	yes	
frost susceptibility classification				
lens formation	yes	yes	no	no
segregation temperature	yes	yes	no	
transient/stationary/long term	t.s and l	t.s and l	t.s and l	
soils	clay and silt with some sand	clay and silt with some sand	clay and silt, trace sand	Ohya Turf
undisturbed/remoulded	undisturbed	undisturbed	undisturbed	?
lead spheres with thermocouples	yes, 15	yes, 14	no	
x-rays	yes, 136	yes, 74	no	
comments				

TABLE A.1 SMALL SCALE FROST HEAVE EXPERIMENTS COMPARISON (PAGE 2 OF 3)

	A5	A6	A9	A11
Frost heave experiments reference nr. author(s)	Akagawa et al. 1985	ASTM D6918-96	Hazen et al. 1983	Ishizaki and Nishio 1988
purpose	empirical formula for stationary heave	frost susceptibility determination	frost heave prediction	validation frost heave prediction model of Miller 1978
length of column (m)	0.016-0.25	0.1651	?	0.054
diameter of column (m)	0.06	0.146	?	0.125
number of layers	?	6		
dry density (kg/m <sup>3</sup> )		initial and final		1500
wet density (kg/m <sup>3</sup> )		initial and final		1980
water content		initial and final		
porosity		field condition		0.487, 0.348
saturation (%)				
temperature top (°C)	warm: 0.2-5	cold: -3, -3, -12,12,3,-3,-12,12,3		warm, T <sub>0</sub> is 1, T <sub>0</sub> is 2.5 to 10
number of temperature sensors	?	8		11
temperature bottom (°C)	cold: -0.8 to -20	warm: -3,3,0,3,3,3,0,3,3		cold, T <sub>0</sub> is 1
open system	yes	when low water table field conditions exist		yes
closed system	no	when low water table field conditions exist		no
initializing ice nucleation	no	no		yes
ramped freezing	N/A	N/A		warm end and cold end -0.025, -0.05, -0.1, -0.2 and -0.4
step freezing	1 step	2 steps		no
temperature step (°C)	?	from 3 to -3 to -12		N/A
duration step (hr)	?	resp 24, 8 and 18		N/A
temperature control bath (°C)	yes	yes		
temperature control chamber (°C)	?	2		1
freeze-thaw cycles	1 freezing	24 lead time, 24 freezing, 24 thawing, 24 freezing, 24 thawing		1 freezing
test duration (hr)	100-1000	120		100
water supply	yes	yes		
constant head	yes	yes	0.10 m on top of the soil	
pore water pressure measurement	no	no		
surcharge (kPa)	60, 110 and 160	0.7	9	170 + 50 back pressure
displacement measurement	yes	no		
SP vs. time (K and M or Nixon method)	yes	possible, but not required		yes
temperature profile at time t	yes	yes		yes
frost heave vs. time	yes	yes		yes
frost penetration vs. time		possible, but not required		yes
water intake vs. time		yes		yes
final water content profile		yes		yes
frost susceptibility classification		no		
lens formation		no		
segregation temperature		no		
transient/stationary/long term		no		
soils	ts and l	clay and silt, trace sand		clay and silt
undisturbed/remoulded	undisturbed	undisturbed		undisturbed
lead spheres with thermocouples	no			yes, 8 without thermocouples
x-rays				yes
comments		should not be used for frost heave prediction		

TABLE A.1 SMALL SCALE FROST HEAVE EXPERIMENTS COMPARISON (PAGE 3 OF 3)

Frost heave experiments reference nr.	A12	A15	A20	A26
author(s)	Ito et al. 1998	Konrad 1987	Nakano and Horiguchi 1985	Penner and Eldred 1985
purpose	segregation potential determination	segregation potential determination	validation of phase equilibrium	DBR/IRC standard
length of column (m)	0.08 to 0.1	Penner 1986	0.016	
diameter of column (m)		Penner 1986	0.1025	
number of layers			1480 and 1130	
dry density (kg/m <sup>3</sup> )				
wet density (kg/m <sup>3</sup> )				
water content				
porosity				
saturation (%)	1.5 to 2 times liquid limit			1 or 2 % above liquid limit
temperature top (°C)	warm, T <sub>0</sub> is 0.5 to 1.5, 1.6, 0.6 and 0.4	warm, T <sub>0</sub> =5, -0.16°C/hr first 24 hrs, 0.008°C/hr after; also -0.024°C/hr first 32 hrs, -0.014°C/hr after	cold T?	warm, T <sub>0</sub> optional eg. 0.65
number of temperature sensors	14	10		10
temperature bottom (°C)	cold, pretest 0.5 to 1.5, t <sub>0</sub> is -10 or -3.7, -2.4 and -1.3	cold, T <sub>0</sub> =-0.2, -0.146°C/hr first 24 hrs, -0.008°C/hr after, also T <sub>0</sub> =-0.2, 0.025°C/hr first 32 hrs, -0.014°C/hr after	warm, 0.1	cold T <sub>0</sub> optional eg. -0.35
open system			yes	
closed system				
initializing ice nucleation				
ramped freezing	no	see T bottom and T top	? Constant heat removal	cold side -10 yes
ramp rate (°C/hr)	no	see T bottom and T top		optional e.g. -0.00083
step freezing	yes	1 freezing	No	no
temperature step (°C)	1 step	warm end 2, cold end -4		N/A
duration step (hr)		22	yes	N/A
temperature control bath (°C)			yes	0.1
temperature control chamber (°C)			yes	
freeze-thaw cycles	1 freezing			1, only freezing
test duration (hr)	50	100-120	2 to 2.5	267 up to 800
water supply		yes	yes	from top
constant head			yes	
pore water pressure measurement		no	no	
surcharge (kPa)	45	50	no	
displacement measurement		yes	yes	X-rays used to locate ice growth
SP vs. time (K and M or Nixon method)	Yes, K and M	yes	yes	no
temperature profile at time t	Yes	yes		yes
frost heave vs. time	yes	yes	yes	yes
frost penetration vs. time	yes	yes	yes	yes
water intake vs. time	yes	yes	yes	yes
final water content profile	yes	yes	yes	yes
frost susceptibility classification	possible	possible		possible
lens formation	no	yes		yes
segregation temperature	yes	yes		
transient/stationary/long term				
soils				
undisturbed/remoulded				
lead spheres with thermocouples				
x-rays				
comments			Morin clay and Fox tunnel silt	

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**APPENDIX B**

**FROST HEAVE PREDICTION MODELS  
LISTING AND COMPARISON**

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**FROST HEAVE PREDICTION MODEL REFERENCE LIST**

(the publications printed in bold are summarized in Table B.1)

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- B2. Berg, R.L., Gartner, K.E., and Guymon, G.L., 1977. A mathematical model to predict frost heave. International Symposium on Frost Action in Soils, Lulea, Vol. 2, pp. 92-109.
- B3. Black, P.B., 1995. RIGIDICE Model of secondary heave. CRREL Report 95-12, 32p.**
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- B5. Blanchard, D., and Frémond, M., 1985. Soils frost heaving and thaw settlement. Ground Freezing 85, Fourth International Symposium on Ground Freezing, Sapporo, S. Kinoshita and M. Fukuda eds., A.A. Balkema, Rotterdam, pp. 209-216.**
- B6. Cary, J.W., and Mayland, H.F., 1987. A new method for calculating frost heave including solute effects. Water Resources Research, Vol. 23, No. 8, pp. 1620-1624.**
- B7. Chang, Y., 1993. An integrated experimental numerical frost heave prediction model. Unpublished M.Eng. thesis, Carleton University, Ottawa, 119 p.
- B8. Derjaguin, B.D., and Churaev, N.V., 1978. The theory of frost heaving. Journal of Colloid and Interface Science, Vol. 67, No. 3, pp. 391-396.
- B9. Derjaguin, B.D., and Churaev, N.V., 1986. Flow of non-freezing water interlayers and frost heaving. Cold Regions Science and Technology, Vol. 12, pp. 57-66.
- B10. Dudek, S.J.M., and Holden, J.T., 1979. A theoretical model for frost heave. Proceedings of the First International Conference on Numerical Methods in Thermal Problems, Swansea, pp. 216-229.**
- B11. Duquennoi, C., Frémond, M., and Levy, M., 1989. Modelling of thermal soil behaviour. VTT Symposium 95, Saariselka, H. Rathmayer ed., Technical Research Centre of Finland, Espoo, pp. 895-915.**
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- B15. Fowler, A.C., 1989. Secondary frost heave in freezing soils. Society for Industrial and Applied Mathematics Journal of Applied Mathematics, Vol. 49, pp. 991-1008.
- B16. Fowler, A.C., and Noon, C.G., 1993. A simplified numerical solution of the Miller model of secondary frost heave. Cold Regions Science and Technology, pp. 327-336.**
- B17. Fowler, A.C., and Krantz, W.B., 1994. A generalized secondary frost heave model. Society for Industrial and Applied Mathematics Journal of Applied Mathematics, Vol. 54, No. 6, pp. 1650-1675.**
- B18. Frémond, M., and Mikkola, M., 1993. Thermo-mechanical model of freezing soil. In: Gas Pipelines, Oil pipelines and Civil Engineering and Arctic Climates, Proceedings of a Seminar held in Caen and Paris, France. Geotechnical Science Laboratories, Ottawa, pp. 48-60.
- B19. Fukuda, M., and Nakagawa, S., 1985. Numerical analysis of frost heaving based upon the coupled heat and water flow model. Ground Freezing 85, Fourth International Symposium on Ground Freezing, Sapporo, S. Kinoshita and M. Fukuda eds., A.A. Balkema, Rotterdam, pp. 109-117.**
- B20. Gilpin, R.R., 1980. A model for the prediction of ice lensing and frost heave in soils. Water Resources Research, Vol. 16, No. 5, pp. 918-930.**
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- B25. Guymon, G.L., Berg, R.L., and Hromadka, T.V., 1993. Mathematical model of frost heave and thaw settlement in pavements. CRREL Report 93-2, 126 p.**
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- B33. Henry, K., 1988. Chemical aspects of soil freezing. CRREL Report 88-7, 15 p.
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- B35. Holden, J.T., 1991. Towards a three-dimensional model of frost heave. Ground Freezing 91, Sixth International Symposium on Ground Freezing, Beijing, X. Yu and C. Wang eds., A.A. Balkema, Rotterdam, pp. 231-235.**
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- B37. Holden, J.T., Piper, D., and Jones, R.H., 1985. Some developments of a rigid ice model of frost heave. *Ground Freezing 85, Fourth International Symposium on Ground Freezing, Sapporo, S. Kinoshita and M. Fukuda eds., A.A. Balkema, Rotterdam, Vol. 1, pp. 93-99.***
- B38. Hopke, S.W., 1980. A model for frost heave including overburden. *Cold Regions Science and Technology, Vol. 3, No. 2, pp. 111-127.***
- B39. Horiguchi, K., 1987. An osmotic model for soil freezing. *Cold Regions Science and Technology, Vol. 14, pp. 13-22.***
- B40. Horiguchi, K., and Nakano, Y., 1993. An osmotic model for soil freezing. *Proceedings of the Fourth International Symposium on Thermal Engineering and Science for Cold Regions, Hanover, CRREL Special Report 93-22, pp. 17-23.*
- B41. Hromadka, T.V., Guymon, G.L., and Berg, R.L., 1981. Some approaches to modelling phase change in freezing soils. *Cold Regions Science and Technology, Vol. 4, pp. 137-145.*
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- B56. Miller, R.D., 1978. Frost heaving in non-colloidal soils. *Permafrost, Third International Conference, Proceedings*, Edmonton, pp. 708-713.
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- B58. Miller, R.D., 1980. Freezing phenomena in soils. *Applications of soil physics*, Hillel, D., ed. Academic Press, New York, pp. 254-299.
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- B63. Nakano, Y., and Takeda, K., 1990. Evaluation of existing hypotheses used in the mathematical description of ice segregation in freezing soils. Fifth international colloquium on free boundary problems, Montreal.
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- B98. Vignes, M., and Dijkema, K.H., 1974. A model for the freezing of water in a dispersed medium. *Journal of Colloid and Interface Science*, Vol. 49, No. 2, pp. 165-172.

TABLE B.1 FROST HEAVE PREDICTION MODEL COMPARISON (PAGE 1 OF 6)

Frost heave prediction model reference nr	B1	B3	B5	B6	B10	B11
Author(s)	Arakawa 1966	Black 1995	Blanchard and Fremont 1985	Cary and Mayland 1987	Dudek and Holden 1979	Duquenoil et al. 1989
Ice formation	Yes	Yes	Yes	Yes	Yes	Yes
Pore ice	No			Yes	Yes	Yes
Ice lens	Yes	Yes	No	Yes		No
Rhythmic Banding	No	Yes	No	No		No
Freezing fringe	No	Yes	No	No	No	No
Thermal gradient	Yes	Yes	Yes	Yes		
Fourier equation	Yes	Yes	Yes	Yes	Yes	Yes
Energy continuity equation	Yes	Yes	Yes	Yes	Yes	Yes
General heat transfer equation	Yes					
Diffusion form of general heat transfer equation	No					
Moisture content gradient	Yes	Yes	Yes	Yes		
Matrix potential gradient	No		No	Yes		
Elevation potential gradient	No	No	No	No		
Vapor pressure	No	No	Yes	Yes		No
Osmotic potential gradient	No	No	No	Yes	No	No
Darcy equation	Yes	Yes	Yes	Yes	Yes	No
Mass continuity equation	Yes	Yes	Yes	Yes	Yes	Yes
General water transport equation						
Diffusion form of general water transport equation	Yes					
Capillary pressure	No	Yes	No	Yes	Yes	No
Surface tension	No	No	No	Yes	Yes	No
Thermodynamic equilibrium	Yes	Yes	sort of	No		Yes?
Clausius-Clapeyron equation	No	Yes	No	No	Yes	sort of
Irreversible thermodynamics	No	No	No	No		No
Criterion for a new ice lens	No	Yes	No	No	No	No
Stress development	No	No	Yes	No	No	No
Validation	No	No	No	Yes	Yes, by own exp., not great	No
Class	2bN	2bFTCRM	2bSM	2bM	2bM	2bSM

CLASSIFICATION LEGEND

- 1 Frost Heave Driving Force Models
  - 1a Capillary driving force models
  - 1b Adsorption driving force models
- 2 Frost Heave Prediction Models
  - 2a Statistical Frost Heave Models
  - 2b Deterministic Frost Heave Models
    - F=Frozen fringe; T=Thermodynamic equilibrium; C=Frost heave criterion; R=Regulation; S=Stress analysis; M=Mechanistic; N=Non-mechanistic



TABLE B.1 FROST HEAVE PREDICTION MODEL COMPARISON (PAGE 2 OF 6)

Frost heave prediction model reference nr	B12	B13	B14	B16	B17	B19
Author(s)	Everett 1961	Forland and Røtjue 1980	Forland 1980	Fowler and Noon 1993	Fowler and Krantz 1994	Fukuda and Nakagawa 1985
Ice formation	Yes	Yes	Yes	Yes	Yes	Yes
Pore ice	No	No	No	Yes	Yes	No
Ice lens	Yes	No	No	Yes	Yes	No
Rhythmic Banding	No	No	No	Yes	Yes	No
Freezing fringe	No	No	No	Yes	Yes	No
Thermal gradient	No	Yes	Yes	Yes	Yes	Yes
Fourier equation	No	No	No	Yes	Yes	Yes
Energy continuity equation	No	No	No	Yes	Yes	Yes
General heat transfer equation	No	No	No	Yes	Yes	Yes
Diffusion form of general heat transfer equation	No	No	No	No	No	No
Moisture content gradient	No	No	No	No	No	No
Matrix potential gradient	No	No	No	Yes	Yes	Yes
Elevation potential gradient	No	No	No	Yes	Yes	Yes
Vapor pressure	No	No	No	No	No	No
Osmotic potential gradient	No	No	No	No	No	No
Darcy equation	No	No	No	Yes	Yes	Yes
Mass continuity equation	No	No	No	Yes	Yes	Yes
General water transport equation	No	No	No	Yes	Yes	No
Diffusion form of general water transport equation	No	No	No	Yes	Yes	Yes
Capillary pressure	Yes	No	No	Yes	Yes	No
Surface tension	Yes	No	No	No	No	No
Thermodynamic equilibrium	Yes	No	No	Yes	Yes	No
Clausius-Clapeyron equation	sort of	No	No	Yes	Yes	No
Irreversible thermodynamics	No	Yes	Yes	No	No	No
Criterion for a new ice lens	No	No	No	Yes	Yes	No
Stress development	No	No	No	No	No	No
Validation	some, Penner 1958, 1959	No	No	No	No	Yes, but an adjustment is included
Class	1a	Not a working frost heave model, leading up to	Not a working frost heave model, leading up to	2bFTCRN	2bFTCRN	2bM

## CLASSIFICATION LEGEND

- 1 Frost Heave Driving Force Models  
 1a Capillary driving force models  
 1b Adsorption driving force models
- 2 Frost Heave Prediction Models  
 2a Statistical Frost Heave Models  
 2b Deterministic Frost Heave Models
- F=Frozen fringe; T=Thermodynamic equilibrium; C=Frost heave criterion; R=Regulation;  
 S=Stress analysis; M=Mechanistic; N=Non-mechanistic

TABLE B.1 FROST HEAVE PREDICTION MODEL COMPARISON (PAGE 3 OF 6)

Frost heave prediction model reference nr.	B20	B21	B22	B25	B26	B27
Author(s)	Gilpin 1980	Gold 1957	Gorelik and Kolumin 2000	Guymon et al. 1993	Guymon et al. 1981	Guymon et al. 1981
Ice formation	Yes	Yes	Yes	Yes	Yes	Yes
Pore ice	Yes	Yes	Yes	Yes	Yes	Yes
Ice lens	Yes	Yes	Yes	Yes	Yes	Yes
Rhythmic Banding	Yes	No	No			
Freezing fringe	Yes	No	Yes			
Thermal gradient	Yes	Yes	Yes	Yes	Yes	Yes
Fourier equation	Yes	No	Yes	Yes	Yes	Yes
Energy continuity equation	Yes	No	Yes	Yes	Yes	Yes
General heat transfer equation	Yes	No	Yes	Yes	Yes	Yes
Diffusion form of general heat transfer equation		No				
Moisture content gradient		No				
Matrix potential gradient	Yes	No				
Elevation potential gradient	Yes	No				
Vapor pressure	No	No	No	No	No	
Osmotic potential gradient	No	No	No	No	No	
Darcy equation	sort of	No	Yes	Yes	Yes	Yes
Mass continuity equation	Yes	No	Yes	Yes	Yes	Yes
General water transport equation		No	Yes	Yes	Yes	Yes
Diffusion form of general water transport equation		No	No			
Capillary pressure	Yes	Yes	No	No		
Surface tension	Yes	Yes	No	No		
Thermodynamic equilibrium	Yes	Yes	Yes	No	Yes	Yes
Clausius-Clapeyron equation	sort of	sort of	Yes	No	Yes	Yes
Irreversible thermodynamics	No	No	No	No		
Criterion for a new ice lens	Yes	No	No	No		
Stress development	No	No	some	some		
Validation	No	No	No	Yes, lab CRREL, Kinoshita (1978), field	Yes, fudging was necessary	
Class	2bFTCM	1a	2bFTRN	2bM	2bN	2a/2bM

## CLASSIFICATION LEGEND

1 Frost Heave Driving Force Models

1a Capillary driving force models

1b Adsorption driving force models

2 Frost Heave Prediction Models

2a Statistical Frost Heave Models

2b Deterministic Frost Heave Models

F=Frozen fringe; T=Thermodynamic equilibrium; C=Frost heave criterion; R=Regulation;

S=Stress analysis; M=Mechanistic; N=Non-mechanistic

TABLE B.1 FROST HEAVE PREDICTION MODEL COMPARISON (PAGE 4 OF 6)

Frost heave prediction model reference nr	B30	B31	B34	B35	B36	B37
Author(s)	Guymon and Luthin 1974	Hartan 1973	Holden 1983	Holden 1991	Holden et al. 1981	Holden et al. 1985
Ice formation	Yes	Yes	Yes	Yes	Yes	Yes
Pore ice	Yes	Yes	Yes	Yes	Yes	Yes
Ice lens	No		Yes	Yes	Yes, depending on time and space steps?	Yes
Rhythmic Banding	No	No	Yes	Yes	No	Yes
Freezing fringe	No	No	Yes	Yes	No	Yes
Thermal gradient	Yes	Yes	Yes	Yes	Yes	Yes
Fourier equation	Yes	Yes	Yes	Yes	Yes	Yes
Energy continuity equation	Yes	Yes	Yes	Yes	Yes	Yes
General heat transfer equation	Yes	Yes	Yes	Yes	Yes	Yes
Diffusion form of general heat transfer equation						
Moisture content gradient						
Matrix potential gradient		Yes				
Elevation potential gradient		Yes				
Vapor pressure	No	Yes	No	No	No	No
Osmotic potential gradient	No	No	No	No	No	No
Darcy equation	Yes	Yes	Yes	Yes	Yes	Yes
Mass continuity equation	Yes	Yes	Yes	Yes	Yes	Yes
General water transport equation	Yes	Yes	Yes	Yes	Yes	Yes
Diffusion form of general water transport equation						
Capillary pressure			Yes	Yes	Yes	Yes
Surface tension		No	Yes	Yes	Yes	Yes
Thermodynamic equilibrium	Yes	sort of	Yes	Yes	Yes	Yes
Clausius-Clapeyron equation	Yes	no ice term	Yes	Yes	Yes	Yes
Irreversible thermodynamics	No	No	No	No	No	No
Criterion for a new ice lens	No	No	Yes	Yes	Yes, a constant seg- temperature	Yes
Stress development	No	No	No	No	No	No
Validation	No	No heave predicted	No	No	Yes, overpredictio n	No
Class	2bM	2bM	2bFTRN	2bFTRN	2bN	2bFTRN

CLASSIFICATION LEGEND	
1 Frost Heave Driving Force Models	2 Frost Heave Prediction Models
1a Capillary driving force models	2a Statistical Frost Heave Models
1b Adsorption driving force models	2b Deterministic Frost Heave Models
	F=Frozen fringe; T=Thermodynamic equilibrium; C=Frost heave criterion; R=Regulation;
	S=Stress analysis; M=Mechanistic; N=Non-mechanistic

TABLE B.1 FROST HEAVE PREDICTION MODEL COMPARISON (PAGE 5 OF 6)

Frost heave prediction model reference nr	B38	B39	B64	B65	B73	B82
Author(s)	Hopke 1980	Horiguchi 1987	Nixon 1991	Nixon 1991	Padilla and Villeneuve 1990	Shen and Ladanyi 1987
Ice formation	Yes	Yes	Yes	Yes	Yes	Yes
Pore ice	No	No		Yes	Yes	
Ice lens	No	Yes		Yes	Yes	
Rhythmic banding	No			Yes	Yes	Yes, but not true to reality
Freezing fringe	No	Yes		Yes	Yes	Yes
Thermal gradient	Yes	Yes	Yes	Yes	Yes	Yes
Fourier equation	Yes	Yes	Yes	Yes	Yes	Yes
Energy continuity equation	Yes	Yes		Yes	Yes	Yes
General heat transfer equation	Yes			Yes	Yes	Yes
Diffusion form of general heat transfer equation						
Moisture content gradient						
Matrix potential gradient						Yes
Elevation potential gradient						Yes
Vapor pressure	No	Yes		No	No	No
Osmotic potential gradient	No	Yes		No	Yes	No
Darcy equation	Yes	Yes		Yes	Yes	Yes
Mass continuity equation	Yes	Yes		Yes	Yes	Yes
General water transport equation	Yes			Yes	Yes	Yes
Diffusion form of general water transport equation				No		
Capillary pressure	Yes	Yes		No		
Surface tension	Yes	No		No		
Thermodynamic equilibrium	Yes	Yes		Yes	Yes	Yes
Clausius-Clapeyron equation	Yes	Yes		Yes	Yes	Yes
Irreversible thermodynamics	No	No	No	No	No	No
Criterion for a new ice lens	No	No	No	Yes, Papp which is adjusted after test results	Yes	Yes, ice content 85% of porosity
Stress development	No	No	No	No	No	Yes
Validation	Yes, Penner and Ueda (1978)	No	Yes, overpredictio n 20-30%	Yes, Penner (1986), Konrad (1988), Ishizaki and Nishio (1988), Konrad (1989)	Yes, field (Quebec City pavement)	Yes, Penner 1988
Class	2bN	2bFTM	2a	2bFTCM	2bFTM	2bFTSN

CLASSIFICATION LEGEND

- 1 Frost Heave Driving Force Models
- 1a Capillary driving force models
- 1b Adsorption driving force models
- 2 Frost Heave Prediction Models
- 2a Statistical Frost Heave Models
- 2b Deterministic Frost Heave Models
- F= Frozen fringe; T=Thermodynamic equilibrium; C=Frost heave criterion; R=Regulation; S=Stress analysis; M=Mechanistic; N=Non-mechanistic



TABLE B.1 FROST HEAVE PREDICTION MODEL COMPARISON (PAGE 6 OF 6)

Frost heave prediction model reference nr	B83	B84	B85		
Author(s)	Shen and Ladanyi 1988	Sheng et al. 1993	Sheng and Knutsson 1993		
Ice formation	Yes	Yes	Yes		
Pore ice		Yes	Yes		
Ice lens		Yes	Yes		
Rhythmic Banding	Yes, but not true to reality	Yes	Yes		
Freezing fringe		Yes	Yes		
Thermal gradient	Yes	Yes	Yes		
Fourier equation	Yes	Yes	Yes		
Energy continuity equation	Yes	Yes	Yes		
General heat transfer equation	Yes	Yes	Yes		
Diffusion form of general heat transfer equation					
Moisture content gradient					
Matrix potential gradient	Yes	Yes	Yes		
Elevation potential gradient	Yes	Yes	Yes		
Vapor pressure	No	No	No		
Osmotic potential gradient	No	No	No		
Darcy equation	Yes	Yes	Yes		
Mass continuity equation	Yes	Yes	Yes		
General water transport equation					
Diffusion form of general water transport equation	Yes				
Capillary pressure		No	No		
Surface tension		No	No		
Thermodynamic equilibrium	Yes	Yes	Yes		
Clausius-Clapeyron equation	Yes	Yes	Yes		
Irreversible thermodynamics	No	No	No		
Criterion for a new ice lens	Yes, ice content 85% of porosity	Yes	Yes		
Stress development	Yes	No	No		
Validation	Yes, Penner 1986	Yes, field	Yes, Takeda and Nakano 1990, Penner and Ueda 1977, Konrad and Morgenstern		
Class	2bFTCSN	2bFTCM	2bFTCM		

CLASSIFICATION LEGEND

- 1 Frost Heave Driving Force Models
- 1a Capillary driving force models
- 1b Adsorption driving force models
- 2 Frost Heave Prediction Models
- 2a Statistical Frost Heave Models
- 2b Deterministic Frost Heave Models
- F=Frozen fringe; T=Thermodynamic equilibrium; C=Frost heave criterion; R=Regulation;
- S=Stress analysis; M=Mechanistic; N=Non-mechanistic



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**APPENDIX C**

**FROST HEAVE PREDICTION  
FOR BURIED CHILLED GAS PIPELINES  
LISTING AND COMPARISON**

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**FROST HEAVE PREDICTION FOR BURIED CHILLED GAS PIPELINES  
REFERENCE LIST**

(the publications printed in bold are summarized in Table C.1)

- C1. **Bowes, W.H., 1984. Bending stresses in pipe due to frost heave. In: Pipelines and Frost Heave, Proceedings of a seminar at Caen, France, S.R. Dallimore, and P.J. Williams eds., pp. 31-33.**
- C2. Carlson, L.E., 1984. Frost heave and thaw settlement test facilities. In: Pipelines and Frost heave, Proceedings of a seminar at Caen, France, S.R. Dallimore, and P.J. Williams eds., pp. 43-47.
- C3. Carlson, L.E., Elwood, J.R., Nixon, J.F., and Slusarchuk, W.A., 1982. Field test results of operating a chilled, buried pipeline in unfrozen ground. Proceedings of the Fourth Canadian Permafrost Conference, Edmonton, pp. 475-480.
- C4. Carlson, L.E., and Nixon, J.F., 1987. Subsoil investigation of ice lensing at the Calgary, Canada, frost heave test facility. Canadian Geotechnical Journal, Vol. 25, pp. 307-319.
- C5. Chen, X., Schofield, A.N., and Smith, C.C., 1994. Centrifuge modelling of frost heave of pipelines. Ground Freezing 94, Seventh International Symposium on Ground Freezing, Nancy, M. Frémond ed., A.A. Balkema, Rotterdam, Vol. 1, pp. 91-96.
- C6. **Foriero, A., and Ladanyi, B., 1994. Pipe uplift resistance in frozen soil and comparison with measurements. Journal of Cold Regions Engineering, Vol. 8, No. 3, pp. 93-111.**
- C7. **Greene, D.P., and Kettle, R.J., 1993. Soil-pipeline interaction associated with a large diameter chilled pipeline in temperate climates. In: Gas pipelines, oil pipelines and civil engineering in arctic climates, Proceedings of a seminar held in Caen and Paris, France, Carleton University, Ottawa, pp. 25-33.**
- C8. Greene, D.P., Kettle, R.J., and Middleton, E., 1995. Instrumentation and monitoring of large-diameter natural gas pipelines operating at sub-zero temperatures in the United Kingdom. Proceedings of the Fifth International Offshore and Polar Engineering Conference, The Hague, ISOPE, Vol. II, pp. 41-46.
- C9. Huang, S., Akagawa, S., Tanaka, T., Ono, T., Nasu, Y., O'Hashi, K., and Fukuda, M., 2002. Ground temperature variation induced by a buried chilled gas pipeline. Cold Regions Engineering, 11th International Specialty Conference, Anchorage, K.S. Merril ed., ASCE Publications, Reston, VA, pp. 158-169.
- C10. Hwang, C.T., 1977A. On quasi-static solutions for buried pipes in permafrost. Canadian Geotechnical Journal, Vol. 14, pp. 180-192.

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- C11. Hwang, C.T., 1977B. Frost heave design of a chilled gas pipeline. 30<sup>th</sup> Canadian Geotechnical Conference, Saskatoon, pp. V-59-V-88.**
- C12. Kettle, R.J., 1984. Soil – pipeline interaction: A review of the problem. In: Pipelines and frost heave, Proceedings of a seminar at Caen, France, S.R. Dallimore and P.J. Williams eds., Geotechnical Science Laboratories, Carleton University, Ottawa, pp. 35-37.
- C13. Konrad, J.M., and Morgenstern, N.R., 1984. Frost heave prediction of chilled pipelines buried in unfrozen soils. Canadian Geotechnical Journal, Vol. 21, pp. 100-115.**
- C14. Ladanyi, B., and Lemaire, G., 1984. Behaviour of a buried pipeline under differential frost heave conditions. Proceedings of the Canadian Society of Civil Engineers Cold Regions Engineering Specialty Conference, Montreal, pp. 161-176.**
- C15. Ladanyi, B., and Shen, M., 1993. Freezing pressure development on a buried chilled pipeline. Frost in Geotechnical Engineering, A. Phukan ed., A.A. Balkema, Rotterdam, pp. 23-33.**
- C16. Nixon, J.F., 1984. A method for predicting frost heave of buried chilled pipelines. Proceedings of a seminar on pipelines and frost heave, Caen, S.R. Dallimore, and P.J. Williams eds., Carleton University, Ottawa, pp. 55-60.**
- C17. Nixon, J.F., 1986. Pipeline frost heave prediction using a 2-D thermal model. In: Research on Transportation Facilities in Cold Regions, O.B. Andersland, and F.H. Sayles eds., ASCE, New York, pp. 67-82.
- C18. Nixon, J.F., 1987a. Pipeline frost heave prediction using the segregation potential frost heave method. Proceedings of the Offshore Mechanics and Arctic Engineering (OMAE) Conference, Houston, pp. 1-6.
- C19. Nixon, J.F., 1987b. Thermally induced frost heave beneath chilled pipelines in frozen ground, Canadian Geotechnical Journal, Vol. 24, pp. 260-266.
- C20. Nixon, J.F., 1992a. New frost heave prediction model for design of northern pipelines. Proceedings of the Second (1992) International Offshore and Polar Engineering Conference, San Francisco, ISOPE, Vol. II, pp. 32-39.**
- C21. Nixon, J.F., 1992b. Discrete ice lens theory for frost heave beneath pipelines. Canadian Geotechnical Journal, Vol. 29, pp. 487-497.**

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- C22. Nixon, J.F., 1994. Role of frost heave pressure dependency and soil creep in stress analysis for pipeline frost heave. Proceedings of the 7th International Cold Regions Engineering Specialty Conference, Edmonton, pp. 397-412.
- C23. Nixon, J.F., and Hazen, B., 1993. Uplift resistance of pipelines buried in frozen ground. Permafrost, Sixth International Conference, Proceedings, Beijing, Vol. 1, pp. 494-499.
- C24. Nixon, J.F., and MacInnes, K., 1996. Application of pipe temperature simulator for Norman Wells oil pipeline. Canadian Geotechnical Journal, Vol. 33, pp. 140-149.
- C25. Nixon, J.F., Morgenstern, N.R., and Reesor, S.N., 1983. Frost heave - pipeline interaction using continuum mechanics, Canadian Geotechnical Journal, Vol. 20, pp. 251-261.**
- C26. Nixon, J.F., Sortland, K.A., and James, D.A., 1990. Geotechnical aspects of northern gas pipeline design. Proceedings of the Fifth Canadian Permafrost Conference, Quebec, Collection Nordicana 54, pp. 299-307.**
- C27. Nixon, J.F., Stuchly, J., and Pick, A.R., 1984. Design of Norman Wells pipeline for frost heave and thaw settlement. Proceedings of the Third International Offshore and Arctic Engineering Symposium, New Orleans, ASME, 8 p.
- C28. Northern Engineering Services Company Limited, 1975. Mechanical Stress Analysis of Buried Pipeline. Report prepared for Canadian Arctic Gas Study Limited, Calgary, 269 p.
- C29. Nyman, K.J., and Lara, P., 1986. Structural monitoring concepts for arctic pipelines. In: Research on Transportation Facilities in Cold Regions, O.B. Andersland, and F.H. Sayles eds., ASCE, New York, pp. 47-66.
- C30. Rajani, B., and Morgenstern, N.R., 1993. Stress history and vertical displacement matching for the pipeline at Caen, France, subjected to frost heave. In: Gas pipelines, oil pipelines and civil engineering in arctic climates, proceedings of a seminar held in Caen and Paris, France, Carleton University, Ottawa, pp. 34-47.
- C31. Rajani, B., and Morgenstern, N.R., 1994. Comparison of predicted and observed responses of pipeline to differential frost heave. Canadian Geotechnical Journal, Vol. 31, pp. 803-816.
- C32. Razaqpur, A.G., and Wang, D., 1996. Frost induced deformations and stresses in pipelines, Journal of Pressure Vessels and Piping, Vol. 69, No. 2, pp. 105-118.

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- C33. Riseborough, D.W., Williams, P.J., and Smith, 1993. Pipelines buried in freezing soil: A comparison of two ground-thermal conditions. Proceedings of the Offshore Mechanics and Arctic Engineering (OMAE) Conference, Vol. V, pp. 183-193.**
- C34. Selvadurai, A.P.S., 1992a. Soil - pipeline interaction at a frost heave zone. Proceedings of the 11th International Conference on Offshore Mechanics and Arctic Engineering (OMAE), Calgary, ASME, New York, Vol. V-B, pp. 337-348.**
- C35. Selvadurai, A.P.S., 1992b. The uplift behaviour of a rigid pipe embedded in a creep susceptible frozen soil. Proceedings of the 11th International Conference on Offshore Mechanics and Arctic Engineering (OMAE), Calgary, ASME, New York, Vol. V-B, pp. 349-357.**
- C36. Selvadurai, A.P.S., Hu, J. and Konuk, I., 1999a. Computational modelling of frost heave induced soil-pipeline interaction I. Modelling of frost heave, Cold Regions Science and Technology, Vol. 29, pp. 215-228.**
- C37. Selvadurai, A.P.S., Hu, J. and Konuk, I., 1999b. Computational modelling of frost heave induced soil-pipeline interaction II. Modelling of experiments at the Caen test facility, Cold Regions Science and Technology, Vol. 29, pp. 229-257.**
- C38. Selvadurai, A.P.S., and Sepehr, K., 1997. Discrete element modelling of pipe uplift in frozen ground regimes. Ground Freezing 97 – Frost Action in Soils, Eighth International Symposium on Ground Freezing, Lulea, Sweden, S. Knutsson ed. A.A. Balkema, Rotterdam, pp. 345-358.**
- C39. Selvadurai, A.P.S., and Shinde, S.B., 1993. Frost heave induced mechanics of buried pipelines, Journal of Geotechnical Engineering, ASCE, Vol. 119, No.12, 1929-1951.**
- C40. Shah, K., 1990. Deformations and stresses in pipelines buried in freezing ground. Unpublished M.Eng. thesis, Carleton University, Ottawa, 149 p.**
- C41. Shah, K., and Razaqpur, A.G., 1993. A two dimensional frost heave model for buried pipelines. International Journal for Numerical Methods in Engineering, Vol. 36, pp. 2545-2566.**
- C42. Sharma, D., and Pralong, P.-J., 1982. Transient freezing and thawing of soils around buried pipelines. Numerical Models in Geomechanics, International Symposium on Numerical Models in Geomechanics, Zurich, R. Dungar, G.N. Pande, and J.A. Studer eds., A.A. Balkema, Rotterdam, pp. 513-524.**
- C43. Shen, M., and Ladanyi, B., 1991. Soil-pipeline interaction during frost heave around a buried chilled pipeline. Cold Regions Engineering, ASCE 6th Int. Special Conf., ASCE Publications New York, pp. 11-21.**

- C44. Slusarchuk, W.A., Clark, J.I., Nixon, J.F., Morgenstern, N.R., and Gaskin, P.N., 1978. Field test results of a chilled pipeline buried in unfrozen ground. Permafrost, Third International Conference, Proceedings, Edmonton, NRC Canada, pp. 878-883.
- C45. Smith, M.W., Dallimore, S.R., and Kettle, R.J., 1985. Observations and prediction of frost heave of an experimental pipeline. Ground Freezing 85, Fourth International Symposium on Ground Freezing, Sapporo, Japan, S. Kinosita and M. Fukuda eds., Balkema, Rotterdam, pp. 297-304.**
- C46. Smith, S.L., and Williams, P.J., 1990. Ice lens orientation around a chilled buried pipe. Proceedings of the Fifth Canadian Permafrost Conference, Collection Nordicana No. 54, Laval University, Laval, pp. 83-87.
- C47. Smith, S.L., and Williams, P.J., 1994. Ice lens formation at a silt-sand interface. Canadian Geotechnical Journal, Vol. 32, pp. 488-495.
- C48. Svec, O., 1981. Frost heave control of a chilled gas pipeline. Cold Regions Science and Technology, Vol. 4, pp. 215-225.
- C49. Wang, D., 1994. A coupled thermo-mechanical analysis of pipelines buried in freezing ground. Unpublished M.Eng.-thesis, Carleton University, Ottawa, 210p.
- C50. Williams, P.J., 1980. Design considerations for large-diameter pipelines in cold regions. Ground Freezing 80, Second International Symposium on Ground Freezing, Trondheim, Norwegian Institute of Technology, pp. 1068-1075.

TABLE C.1 FROST HEAVE PREDICTION FOR BURIED PIPELINES COMPARISON (PAGE 1 OF 4)

frost heave prediction for buried pipelines reference nr	C1	C6	C7	C11	C13
author(s)	Bowes 1984	Foriero and Ladanyi 1994	Greene and Kettle 1993	Hwang 1977B	Konrad and Morgenstern 1984
model/no model	no model	no model	no model	model	model
focus	bending stresses in pipeline and strain measurements	pipe uplift resistance	ground cracking above buried pipeline		
frost heave prediction model used	no	no	no		SP
soil response to frost heave		yes	no		
discrete spring(s) or continuum			no	discrete springs	discrete springs
rheology of the surrounding soil		creep and plastic	no		elastic?
2D/3D	no	2D	no	2D	3D
cartesian/polar coordinates	no	polar	no		polar
numerical methods	no		no		
pipe: rigid, complex, free moving	rigid		no		free moving
soil-pipeline interaction	no	bonded and frictionless	no		no

TABLE C.1 FROST HEAVE PREDICTION FOR BURIED PIPELINES COMPARISON (PAGE 2 OF 4)

frost heave prediction for buried pipelines. reference nr	C14	C15	C16	C20	C21
author(s)	Ladanyi and Lemaire 1984	Ladanyi and Shen 1993	Nixon 1984	Nixon 1992a	Nixon 1992b
model/no model	model	model		model	model
focus					
frost heave prediction model used	vertical pile model		SP	Nixon 1991	Nixon 1991
soil response to frost heave		independent linear spring			
discrete spring(s) or continuum				discrete spring	discrete spring
rheology of the surrounding soil					
1D/2D/3D				2D	2D
cartesian/polar coordinates				polar	polar
numerical methods				fin diff	fin diff
pipe: rigid, complex, free moving		rigid, free floating			
soil-pipeline interaction				no	no

TABLE C.1 FROST HEAVE PREDICTION FOR BURIED PIPELINES COMPARISON (PAGE 3 OF 4)

frost heave prediction for buried pipelines reference nr	C25	C26	C33	C34	C35
author(s)	Nixon et al. 1983	Nixon et al. 1990	Riseborough et al. 1993	Selvadurai 1992a	Selvadurai 1992b
model/no model	model	no model	no model	model	
focus		geotechnical aspects of northern gas pipeline design	description Caen experiments 1982-1992	maximum bending moment along pipeline over time at a frozen-non-frozen interface	
frost heave prediction model used	SP	SP		Nixon 1987	
soil response to frost heave	yes	yes			
discrete spring(s) or continuum	continuum	discrete springs		continuum	continuum
rheology of the surrounding soil	elastic or non-linear viscous			vol. strain, elastic, creep	vol. strain, elastic, creep, creep damage
2D/3D		1D/2D		2D	
cartesian/polar coordinates					
numerical methods					
pipe: rigid, complex, free moving		non-linear, elastic-plastic, viscous		1D Bernoulli-Euler beam	
soil-pipeline interaction				bonded	bonded

TABLE C.1 FROST HEAVE PREDICTION FOR BURIED PIPELINES COMPARISON (PAGE 4 OF 4)

frost heave prediction for buried pipelines reference nr	C36	C41	C42	C43	C45
author(s)	Selvadurai et al. 1999a	Shah and Razaqpur 1993	Sharma and Pralong 1982	Shen and Ladanyi 1991	Smith et al.
model/no model	model	model	model	model	model
focus	3D formulation of Shen and Ladanyi 1987 and experimental model calibration	2D formulation of rigid ice model; application to frost heave prediction for pipelines	freezing around a chilled gas pipeline		observations and frost heave prediction using SP
frost heave prediction model used	Shen and Ladanyi 1987	O'Neill and Miller 1985	heat treatment only	Shen and Ladanyi 1987	SP
soil response to frost heave	no	no	no		no
discrete spring(s) or continuum	continuum				discrete spring
rheology of the surrounding soil	no	no		vol. strain, elastic, creep	no
2D/3D	3D	2D			1D
cartesian/polar coordinates	cartesian	cartesian			cartesian
numerical methods	finite elements	finite elements		finite elements	analytical
pipe: rigid, complex, free moving		N/A		rigid, free floating	free moving
soil-pipeline interaction		no	no		no

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**APPENDIX D**

**INSTITUTIONS AND COMPANIES  
ACTIVE IN FROST HEAVE RESEARCH  
IN PAST OR PRESENT**

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**CENTRES OF FROST HEAVE KNOWLEDGE**


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<b>Institution or Company</b>	<b>Location</b>	<b>Practitioners/Researchers</b>
<b>Canada:</b>		
Agriculture Canada	Ottawa	Balchin, Hayhoe
Agriculture Canada	Swift Current	Jame
Carleton University	Ottawa	Burt, Chang, Jetchik, Razaqpur, Riseborough, Schellekens, Selvadurai, Shah, Smith M.W., Smith S., Wang, Williams, Wood
C-CORE	St. John's	Clark, Kenny, Morgan
EBA Engineering Consultants Ltd.	Edmonton	Hayley, Horne, Hwang, Jones K., Schellekens, Seto
Environment Canada	Ottawa	Harlan
Foothills Pipe Lines Ltd.	Calgary	Carlson, Ellwood
Geo-engineering Ltd.	Calgary	Saunders
Geological Survey of Canada	Ottawa	Burgess, Dallimore, Konuk, Lawrence, Smith S.
Golder Associates	Calgary	Crooks
R.M. Hardy and Associates/Hardy BBT Ltd./AGRA Earth & Environmental Ltd./AMEC Earth & Environmental Ltd.	Calgary/ Edmonton	Barnes, McRoberts, Oswell, Hanna, Slusarchuk, Van Gassen, Reesor, Nixon
Lakehead University	Thunder Bay	Eigenbrod
L.E.C. Engineering Ltd.	Calgary	Carlson
McGill University	Montreal	Hu, Selvadurai
National Energy Board	Ottawa	Walton

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**CENTRES OF FROST HEAVE KNOWLEDGE**


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<b>Institution or Company</b>	<b>Location</b>	<b>Practitioners/Researchers</b>
National Research Council	Ottawa	Gold, Goodrich, Penner, Rajani Svec, Ueda, Williams
Nixon Geotech Ltd.	Calgary	Nixon
Queen's University	Kingston	Gaskin
Saint Mary's University	Halifax	Tarnawski
Université de Montréal	Montreal	Foriero, Ladanyi, Shen,
Université du Québec	Sainte-Foy	Padilla, Villeneuve
Université Laval	Quebec City	Konrad, Seto, Shen
University of Alberta	Edmonton	Biggar, Gilpin, Horne, Konrad, Mageau, McRoberts, Morgenstern, Murray, Nixon, Rajani, Segó, Van Gassen
University of Guelph	Guelph	Groenevelt, Kay, Perfect
University of Manitoba	Winnipeg	Chandler, Domaschuk
University of Ottawa	Ottawa	Evgin
University of Saskatchewan	Saskatoon	Norum
<b>U.S.A.:</b>		
Battelle Pacific Northwest Laboratory	Richland, WA	Cary
Continental Oil Co.	Ponca City, OK	Radd, Oertle
Cornell University	Ithaca, NY	Black, Bresler, Cass, Dirksen, Hoekstra, Koopmans, Koslow, Miller, Romkens
Dames & Moore	Golden, CO	Sharma, Pralong
Exxon Production Research Company	Houston, TX	Heuer, Hopke, Jahns, Miller T.W., Power, Rickey, Taylor, Wheeler

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**CENTRES OF FROST HEAVE KNOWLEDGE**


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<b>Institution or Company</b>	<b>Location</b>	<b>Practitioners/Researchers</b>
Johns Hopkins University	Baltimore, MD	Michalowski
Northern Engineering & Scientific	Anchorage, AK	Hazen
Ohio State University	Columbus, OH	Taylor
Oregon State University	Corvallis, OR	Vinson
Purdue University	West-Lafayette, IN	Harr, Leonards Low,
Texas A & M University	College Station, TX	Anderson D.M.
U.S. Army Cold Regions Research and Engineering Laboratories	Hanover, NH	Anderson, Berg, Bigl, Black, Chamberlain, Gow, Henry, Hoekstra, Ingersoll, Johnson T.C., Ketcham, McGaw, Nakano, O'Neill, Shoop, Takagi
U.S. Department of Agriculture	Kimberly, ID	Cary
U.S. Geological Survey	Menlo Park, CA	Ferrians, Kachadoorian
University of Alaska	Fairbank, AK	Goering, Guymon, Phukan, Shur, Zarling
University of California	Davis, CA	Berggren, Luthin
University of California	Fullerton, CA	Hromadka
University of California	Irvine, CA	Guymon, Hromadka
University of Colorado	Boulder, CO	Krantz, Peterson
University of Michigan	Ann Arbor, MI	Outcalt
<b>U.K.:</b>		
Aston University	Birmingham	Kettle, Johnson B.D.
British Drilling & Freezing Co. (formerly Foraky)	Nottingham	Harris J.S.

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**CENTRES OF FROST HEAVE KNOWLEDGE**


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<b>Institution or Company</b>	<b>Location</b>	<b>Practitioners/Researchers</b>
British Gas	Solihull	Piper
Transport Research Laboratory	Crowthorne	
University of Bristol	Bristol	Everett
University of Glasgow	Glasgow	Sutherland
University of Leeds	Leeds	Stewart
University of Nottingham	Nottingham	Baba, Dudek, Harris J.S., Holden, Jones R.H., Piper
University of Oxford	Oxford	Fowler, Noon
University of Wales	Swansea	Lewis, Sze
WS Atkins Engineering Sciences	Epsom, Surrey	Piper
<b>France:</b>		
Centre National de la Recherche Scientifique (CNRS)	Caen	Van Vliet-Lanoe
Laboratoire Central des Ponts et Chaussées (LCPC)	Paris	Frémond, Blanchard, Levy, Duquennoi, Livet, Dupas
<b>Germany:</b>		
Ruhr University	Bochum	Ebel, Jagow, Jessberger, Jordan
<b>Netherlands:</b>		
Eindhoven University of Technology	Eindhoven	Biermans, De Vries, Dijkema, Vignes

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**CENTRES OF FROST HEAVE KNOWLEDGE**


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<b>Institution or Company</b>	<b>Location</b>	<b>Practitioners/Researchers</b>
<b>Sweden:</b>		
Swedish Geotechnical Institute	Linköping	Bergau
Technical University of Lulea	Lulea	Axelsson, Knutsson, Pusch, Sheng, Viklander
Uppsala University	Uppsala	Lundin
<b>Norway:</b>		
Norwegian Road Research Laboratory	Oslo	Saetersdal
Norwegian University of Science and Technology	Trondheim	Forland, Frivik, Johansen, Ratkje
<b>Finland:</b>		
Helsinki University of Technology	Helsinki	Aalto, Gustavsson, Hartikainen, Mikkola, Ravaska
Tampere University of Technology	Tampere	Saarelainen
Technical Research Centre of Finland (VTT)	Espoo	Saarelainen, Rathmayer
University of Oulu	Oulu	Kujala, Ravaska
<b>Russia:</b>		
All Union Research Institute for Hydrogeology and Engineering Geology	Moscow	Grechishchev, Pavlov, Ponomarev
Earth Cryosphere Institute SB RAS	Tyumen	Gorelik, Kolunin, Reshetnikov

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**CENTRES OF FROST HEAVE KNOWLEDGE**


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<b>Institution or Company</b>	<b>Location</b>	<b>Practitioners/Researchers</b>
Moscow State University	Moscow	Cheverev, Chuvilin, Ershov, Grigorjan, Guseva, Krass, Magomedgadzhieva, Vidyapin
<b>Japan:</b>		
Ashikaga Institute of Technology	Tochigi	Nishimura
Central Research Institute of Electric Power Industry	Tokyo and Chiba	Ogata, Kataoka
Hokkaido University	Sapporo	Akagawa, Arakawa, Fukuda (Masami), Horiguchi, Ishizaki, Kuroda,
Kitami Institute of Technology	Kitami	Liu, Sawada, Suzuki
Konoike Construction Co.	Osaka	Takeda
Nagaoka University of Technology	Nagaoka	Aoyama, Ogawa
Nippon Koukan Co.	Kawasaki	Nakagawa
Odakyu Construction Co.	Tokyo	Komiya
Seiken Co.	Osaka	Ohrai, Okamoto, Takashi, Yamamoto
Setsunan University	Osaka	Ito
Shimizu Construction Co.	Tokyo	Akagawa, Ryokai
Sumitomo Mitsui Construction Co.	Tokyo	Fukuda
Tokyo Electric Power Co.	Tokyo	Hashimoto, Yamamoto

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**CENTRES OF FROST HEAVE KNOWLEDGE**

<b>Institution or Company</b>	<b>Location</b>	<b>Practitioners/Researchers</b>
Tokyo Gas Co.	Tokyo	Ishizaki, Minami, Miyata, Nishio
<b>China:</b>		
Cold Region Development Institute	Harbin	
Heilongjiang Cold Regions Construction Research Institute	Harbin	
Lanzhou Institute of Glaciology and Cryopedology, Academia Sinica	Lanzhou	Ding, Xu

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**Part 3.**

**Review of large scale northern pipeline test facilities, by J.I. Clark and Associates, St John's**

# **Review of Large Scale Northern Pipeline Test Facilities**

## **Final Report**

### **Prepared for:**

J. I. Clark & Associates

### **Prepared by:**

C-CORE

R-03-087-286 v3.0

June 2004



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# **Review of Large Scale Northern Pipeline Test Facilities**

## **Final Report**

### **Prepared for:**

Geological Survey of Canada

### **Prepared by:**

J. I. Clark & Associates

R-03-19 v3.0  
June 2004

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**Project Team:**

Jack Clark, (Project Manager)  
Vincent Morgan (C-CORE)

## **EXECUTIVE SUMMARY**

This report presents a review by J.I. Clark and Associates of large and full-scale pipeline test facilities constructed and operated to investigate the effects of pipelining in northern regions.

Ten test facilities have been reviewed. The facilities were established to investigate a range of design, construction and operational criteria including frost heave, thaw settlement, geothermal regime, pipe-soil interaction, constructability and revegetation/rehabilitation. The ten sites considered are:

- Caen, France
- Calgary, Alberta
- Fairbanks, Alaska (2)
- Inuvik, NWT
- Mountain River / Sans Sault, NWT
- Nordegg, Alberta
- Norman Wells, NWT
- Prudhoe Bay / Deadhorse, Alaska
- Quill Creek, Yukon

Most of the facilities were initiated in response to proposed pipeline construction projects along the Mackenzie Valley in the early 1970s. Much of this information was submitted to the Northern Pipeline Hearings in 1975 and the reports are publicly available. Other test sites constructed along the proposed Alaska Highway route remain proprietary. More recent test sites include facilities at Caen, France in the 1980s and early 1990s and reactivation of the Foothills test site in 1999.

The results of the review are discussed in the main report text with observations and opinions of relevance. The appendices contain a summary format for each test site including relevant details of main participants, purpose, description of tests, operating conditions, instrumentation, key results and recommendations for further use of the data produced. A detailed bibliography is also included for each test site, from which additional information can be accessed if required. A number of relevant figures and photographs from selected test sites are presented.

Important issues that are not studied at the test sites are identified and recommendations for further studies that could assist in the review process are presented.

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## **1.0 INTRODUCTION**

J.I. Clark & Associates was requested by the Geological Survey of Canada to review all available documentation relating to large and full-scale pipeline tests performed in northern regions and those directly related to northern pipelines undertaken elsewhere. The principal areas of interest are the study of frost heave, thaw settlement, permafrost degradation and pipe-soil interaction arising from construction and operation of large diameter transmission pipelines. This work was led by Dr. Jack Clark, P.Eng., who initiated the large-scale testing at the Calgary test site.

## **2.0 METHODOLOGY**

The majority of information has been obtained through searches of the Arctic Science and Information (ASTIS) system and the University of Calgary library catalogue. The primary source of data was the Arctic Institute of North America (AINA), located in the University of Calgary. Many original reports have been donated to AINA by petroleum and pipeline companies with activities in the north and much of the material is unique to this facility. The archive library of the National Energy Board (NEB) in Calgary was also used to locate reports not available at AINA. In addition, a number of conference proceedings have been reviewed and referenced as part of the study, as they may be more readily available than the original test site reports.

The reports were reviewed and summarized by the project team who are familiar with the issues relating to northern pipelines, as well as by Jack Clark, who has been intimately involved in northern pipeline research activities since the early 1970s. His responsibilities included geotechnical, environmental and route location studies carried out by Northern Engineering Services Ltd (NESL) on behalf of Canadian Arctic Gas Studies Ltd (CAGSL).

## **3.0 BACKGROUND TO LARGE-SCALE TEST SITES**

During the 1960s and 1970s a large amount of natural gas was found in the Canadian and American Arctic. In Canada, Imperial Oil discovered the Taglu field on Richards Island, Shell Canada, the Niglintgak field and Gulf Canada, the Parsons Lake Field. All of these discoveries were considered commercial provided a means of transportation to southern markets was developed.

In the early 1970s, two competing consortia were formed to pursue the building of a gas pipeline from the Mackenzie Valley to markets in southern Canada and the USA. One group, Gas Arctic Systems (GAS), was led by Alberta Gas Trunkline Limited (AGTL). Columbia Gas was among its sponsors. The second group, Northwest Project Group (NPG) was led by Williams Brothers Canada Limited. The sponsors included the producers, a number of gas distributors and pipeline companies such as TransCanada PipeLines, Michigan Wisconsin Gas and Southern California Gas. In 1972, it was made

known to the two consortia that the Federal Government was not enthusiastic about receiving two competing applications for essentially the same pipeline. The two consortia managed to merge, in spite of fundamental differences, to form Canadian Arctic Gas Study Limited (CAGSL).

The engineering work of the GAS Group had been carried out in house with AGTL management of consultants. The Northwest Project Group carried out no in-house engineering but rather contracted with Williams Brothers Canada Limited who in turn engaged a number of sub-consultants. The merged group, under pressure from NPG sponsors created Northern Engineering Services Limited (NESL) to be responsible for all the engineering design, reporting directly to CAGSL. At that time CAGSL had over 20 participating sponsors including most of the major producers and pipeline companies in Canada and the US. NESL was made up of Williams Brothers Canada Limited, Montreal Engineering, Shawinigan Engineering, Teshmont and Hardy Associates.

During the period when the two consortia were operating independently, several test sites were constructed. GAS constructed a test site at Prudhoe Bay, largely driven by Colombia Gas with the Battelle Corporation responsible for engineering and construction. A test site was also constructed at Norman Wells and instrumentation was installed at a looped section of an AGTL line near Nordegg, Alberta. The Northwest Project Group constructed a major test site at Sans Sault Rapids, where the Mountain River joins the Mackenzie. Previous to these test sites a consortia of companies (Mackenzie Valley Pipeline Research Limited (MVPRL)) studying the feasibility of an oil line from the Arctic, constructed a hot oil line test facility near Inuvik, NWT.

CAGSL constructed a frost heave test facility in Calgary, Alberta. The CAGSL line was intended to bring gas from Prudhoe Bay, across Alaska and the Yukon to join with the gas line from the Mackenzie Delta. A competing gas line for Prudhoe Bay was filed by El Paso Gas with the Federal Power Company in the USA to carry gas directly from Prudhoe Bay to Valdez, Alaska where it would be liquefied and transported by LNG tankers to markets in the USA and Japan. El Paso did not construct any test sites but they also proposed a chilled gas line.

The original three chilled gas pipeline test sites at Prudhoe Bay, Norman Wells and Sans Sault Rapids primarily reflected what was at the time the preferred construction mode of the proponents. GAS held the view that a half berm or a full berm with the pipeline and/or the berm insulated was the optimum construction configuration. Hence both Prudhoe Bay and Norman Wells test sites included berms or half berms, typically with insulation. The Quill Creek facility also focused primarily on the use of insulated gravel pads and insulated pipes with the pipeline contained in a large berm. The gas flowed at above freezing temperatures. Elsewhere along the proposed route, short sections of pipeline were buried and chilled to assess potential frost heave.

NGPL held the view that the most secure and environmentally acceptable pipeline would be one fully buried with the spoil mounded over the pipe and the entire right of way re-vegetated and protected from erosion. Insulation was to be avoided, partly because of

cost but also because of the increased buoyancy that would have to be dealt with prior to start up of chilling.

Before public hearings were started, AGTL broke away from CAGSL and filed for a competing pipeline from the Mackenzie Valley. They partnered with West Coast Transmission to form a company called Foothills Pipelines to construct the Maple Leaf Pipeline. Public hearings were held in Yellowknife under the auspices of DIAND (the Berger Commission) and by the NEB in Ottawa and the FPC in Washington. The Berger Commission focused on environmental issues and aboriginal concerns but did not have the authority to approve or reject the application. Approval of the NEB was required to construct the line in Canada. The FPC hearing authority could only recommend a line to the Department of Interior whose approval was required for any Alaska portion.

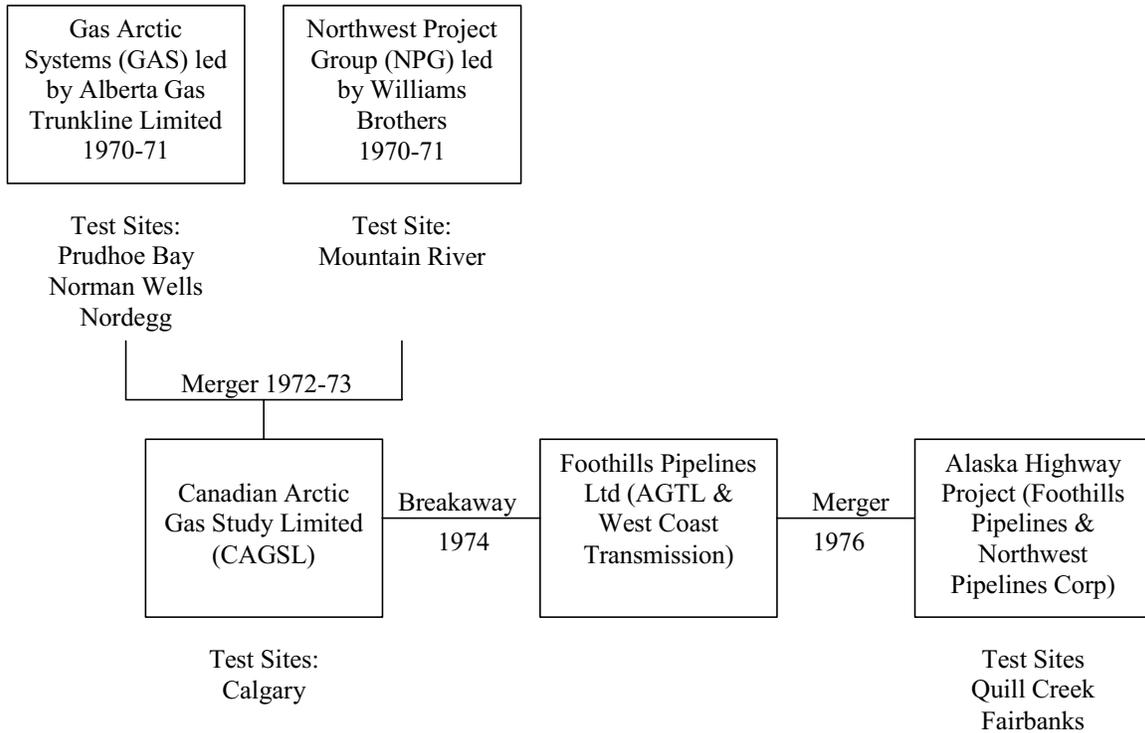
After the Berger Commission was well advanced and NEB and FPC hearings were initiated, a new pipeline application emerged. It was sponsored by a new consortium that included Foothills Pipelines, West Coast Transmission and Northwest Pipeline from the USA. Their proposal was to carry gas (chilled) parallel to the Alyeska Pipeline from Prudhoe Bay to Fairbanks after which it would follow the Alaska Highway to Southern Canada where new pipelines would be built to California and the Northern Border Pipeline. The Mackenzie Delta Gas would be carried by a pipeline that followed the Dempster Highway. The Alaska Highway group did not carry out any studies or engineering design but were nevertheless certificated by the NEB. In the USA, the FPC hearing authority recommended the CAGSL line but their recommendation was overturned by the Department of Interior who approved the Alaska Highway Pipeline. Hence this group was certificated to proceed with construction. The Foothills group then initiated a number of test sites along the proposed route. A large facility was built at Quill Creek in the Yukon and a smaller facility at Fairbanks, Alaska. Several short sections of chilled pipelines were also operated at various points along the routes. Most of this test data remains proprietary and no information is in the public domain.

The Alaska Highway portion of the route was not constructed but the southern legs to the USA were built and operated by Foothills. TCPL acquired this facility and became part of Foothills in partnership with West Transmission when they purchased Nova Corporation (formerly AGTL). Recently TCPL acquired all of Foothills, which now operates as TCPL.

In addition to the full-scale test sites in Canada and Alaska, a test bed was constructed in Caen, France in 1978. This facility was jointly funded by Canadian and French governments. Government funding was also provided for Canadian researchers to use the facility.

In 1999, the Fairbanks test site originally built by Foothills was reactivated by the Japan Science and Technology Corporation. It continues to operate with AMEC Earth & Environmental (formerly Hardy Associates and BBT) providing the engineering services for the start-up and operation.

The relationship between various pipeline proponents and research organizations is shown in Figure 1. All of the known records from these facilities are summarized in the Appendices of this report.



Independent Test Sites:

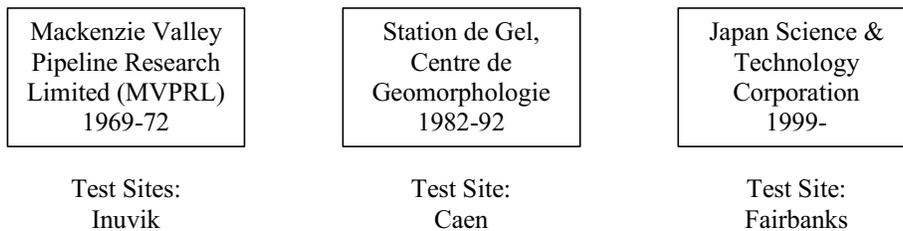


Figure 1: Diagrammatic Representation of Pipeline Proponents and Test Facilities

#### **4.0 DESIGN, ENVIRONMENTAL, SAFETY & SECURITY ISSUES**

The contract included a request that the consultant identify issues that could hinder the design or cause environmental, safety or security concerns that might be a stumbling block for decision makers who will assess an application or for regulators who will oversee its operation.

It is difficult to imagine any major issue that has not been identified and debated at length in one or more of the three major hearings in the 1970's, which were all adversarial. Adversarial applicants and interveners opposed to the project engaged experts and spokespersons to give their opinions and to cross-examine the opinions of others either for or against the pipeline.

A major stumbling block at the time was land claims or what was deemed to be aboriginal rights. These have largely been resolved at this time. The technical issues that received most attention were frost heave, thaw settlement, the point of last chilling, the use of crack arrestors on the pipe, right-of-way erosion and winter construction versus summer construction.

The frost heave/thaw settlement debate centered on whether or not it was preferable to stop chilling the gas near the southern limit of continuous permafrost near Fort Good Hope or to continue chilling, for example, to Norman Wells or indeed, northern Alberta. If the gas chilling did not continue through the discontinuous permafrost zone, extensive thaw settlement would need to be dealt with. If it were chilled through this zone, frost heave was to be a major design consideration.

The existing oil pipeline from Norman Wells to Alberta, operated by Enbridge, has provided a wealth of information on right of way behaviour including such aspects as thaw settlement, slope stability and erosion. An excellent monitoring program has been conducted by GSC and this information is available to regulators and design groups.

Reliable methods of predicting frost heave including analytical methods and experimental modeling are available. Thousands of boreholes have been drilled and reliable terrain maps have been developed. The amount of ground that is frozen or unfrozen can be quantified by geo-physical methods. Frost heave can be controlled for most soil types traversed by burial depth, without exceeding the limit of ditchers already proven in the arctic. The beneficial effect of increased burial depth was demonstrated at the Calgary test site as shown in Figure 2. The issues related to frost heave of chilled gas pipelines nevertheless remain as controversial in some quarters. For example, the continued growth of ice lenses behind the freezing front or the growth of ice lenses in warm permafrost, i.e. permafrost with a high unfrozen water content has been put forward as a concern to pipeline heave. There is no field evidence to support this concept; indeed, the opposite is true. Figure 3 shows pipe movement in permafrost for one of the pipe sections at the Sans Sault Rapids site over a 27 month period. Although a small amount of heave is recorded, it was never more than 0.09 feet (27mm) and the pipe ended up with

an average 0.01 feet (3mm) movement at the end of the test. Movement appears to be related to ground temperature surrounding the pipe.

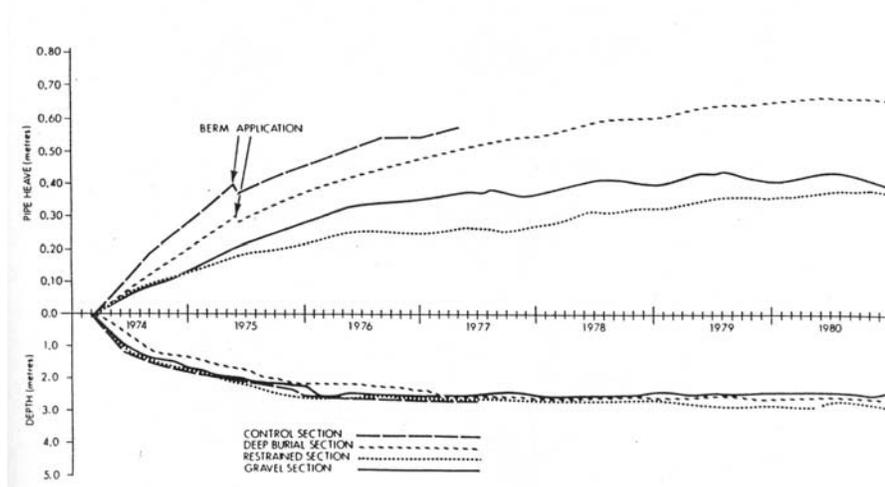


Figure 2: Measured pipeline heave and frost penetration at Calgary test site

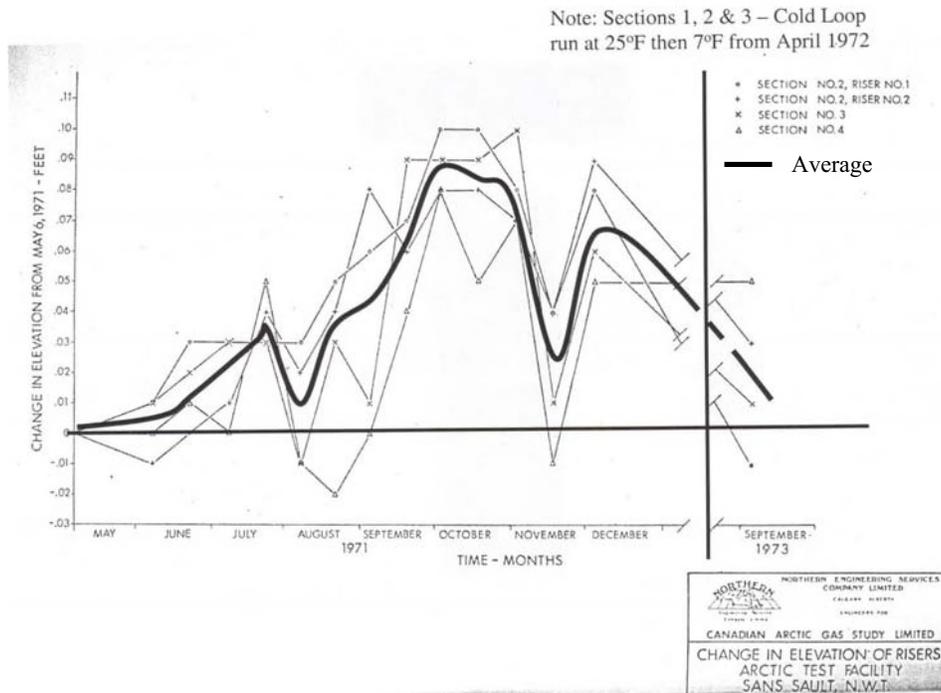


Figure 3: Measured pipe movement at Sans Sault Rapids test site

Similarly, experimental modeling with piezometers to measure suction pressure has shown that when the frost line passes a piezometer, the suction pressure is significantly reduced and is much less than suction pressure ahead of the freezing front. This is shown in Figure 4, where reductions in pore pressure suction are observed as the frost front passes a pore pressure transducer in a model test at approximately 480 minutes and again after a period of thaw at 700 minutes. Hence any migration of unfrozen water would be downward toward the frost front rather than toward the pipeline. Irrespective of direction of flow the permeability of the frozen soil is so low that migration of unfrozen water to or away from the freezing front is insignificant. This issue, which continues to crop up, has no application to practical pipeline problems.

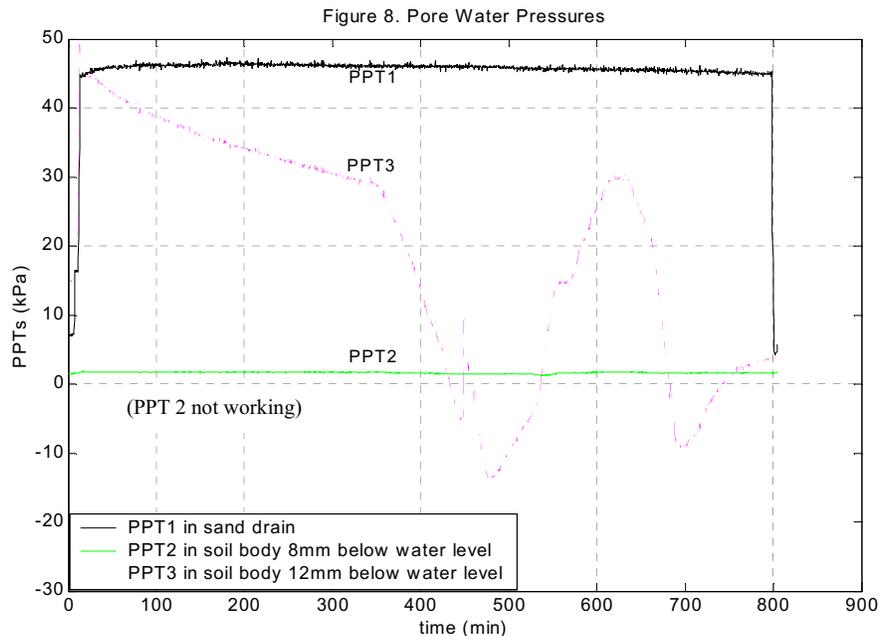


Figure 4: Pore Pressure Response during Progression of the Freezing Front

The substantial advancement in pipeline material properties and welding technology has addressed some of the issues previously presented, such as welding and the use of crack arrestors. It is understood that the current design is based on a smaller diameter pipe than previously considered, operating at a much higher pressure. Much stronger steel is now available for pipelines and it is understood that problems associated with welding very high strength steel and reduced flexibility have been overcome. With previous designs it was concluded that without crack arrestors the pipe could fracture for the full length between compressor stations. It is not known if the same situation would occur with the smaller diameter pipeline and high strength steel.

Winter construction would require snow roads and snow work pads. These may require snow harvesting as well as snow making; depending upon the winter. If snowmaking is required, and it should be assumed that it is, lakes or rivers where water could be

withdrawn without significant environmental impact need to be identified. This may be a challenge for some sections.

Summer construction may be feasible for some of the route where the ground is thaw stable. Environmental impact due to terrain disturbance would be much greater for summer construction. Gravel is generally very scarce in the Mackenzie Valley, with many conflicting demands. Construction of haul roads and work pads for summer construction would draw heavily on scarce granular borrow reserves and would also have a greater and longer lasting impact.

Drainage and erosion control is an important consideration but techniques are available to prevent erosion of the spoil mound and in the ditch as well as erosion of the right of way. Control of erosion of slopes is a challenge but one that can be met with conventional erosion control designs such as sand bag blocks in the ditch and small berms on the right-of-way.

Pipeline pressure testing requires special techniques not normally used and some environmental damage may be experienced if there is a loss of the testing medium.

The timing of construction in environmentally sensitive areas, particularly river crossings, is important. There will be well over 200 minor river crossings and several major crossings. The minor crossings will be more sensitive to environmental disturbance than the major crossings. Directional drilling techniques can be used in those areas where conventional construction is too disruptive to over wintering fish. Insulation may be required to prevent freezing of the bottom of streams and small rivers where icings could occur if the bottom of the river freezes above the pipe. Icings may or may not have an impact depending on where the crossings is located in relation to over wintering or spawning areas and other facilities such as access roads or the existing Mackenzie Valley highway sections.

In summary it is believed that the issues that could cause damage to the environment or result in safety or security concerns have been previously identified and are likely known to the present proponents. There are no known showstoppers or fatal flaws but designs, construction timing and methods and operational procedures must reflect the need to avoid damage. In many cases there will be several alternatives available, which will require engineering judgment to select the most appropriate approach.

## **5.0 PRESENTATION OF DATA**

Ten test sites have been identified as being relevant to this study, in that they involved the construction and operation of a large-scale pipeline test facility, with a primary aim of investigating behaviour due to freezing or thawing of the soil. The results of many of the test sites were proprietary to the proponents at the time but have since been made available to the public domain. The results of some test sites remain unavailable outside of the sponsors' organizations, although details are presented where available.

The test sites were located as follows:

- Caen, France
- Calgary, Alberta
- Fairbanks, Alaska (2)
- Inuvik, NWT
- Mountain River / Sans Sault, NWT
- Nordegg, Alberta
- Norman Wells, NWT
- Prudhoe Bay / Deadhorse, Alaska
- Quill Creek, Yukon

Figure 5 shows the location of the main test sites in relation to proposed pipeline routes. The details of each test site are presented in Appendices A to I. Each Appendix presents the pertinent details of the test sites, including location, participants, objectives, facilities constructed, instrumentation installed and a summary of results where available. Recommendations are made regarding the applicability and usefulness of the data obtained from the test facilities. A fully referenced bibliography of the reports and publications reviewed as part of this study is included for each test site to allow further details to be obtained. Where available, call numbers and brief abstracts have been downloaded from the ASTIS database and are included as part of the reference list.



Figure 5: Location of main test sites in relation to proposed pipeline routes

## 6.0 SIGNIFICANT FINDINGS AT EACH TEST SITE

**Caen, France** - The most useful result from the series of tests in Caen was the pipe deformation at the interface of a non or low frost susceptible soil (sand) and a highly frost susceptible silt. Figure 6 shows the longitudinal section through the test bed and Figure 7 shows the deformation along the section of test pipe at various time intervals. Tests were also performed on a pipeline laid across a frozen and unfrozen interface, but issues relating to thawing of the frozen side at depth made interpretation difficult.

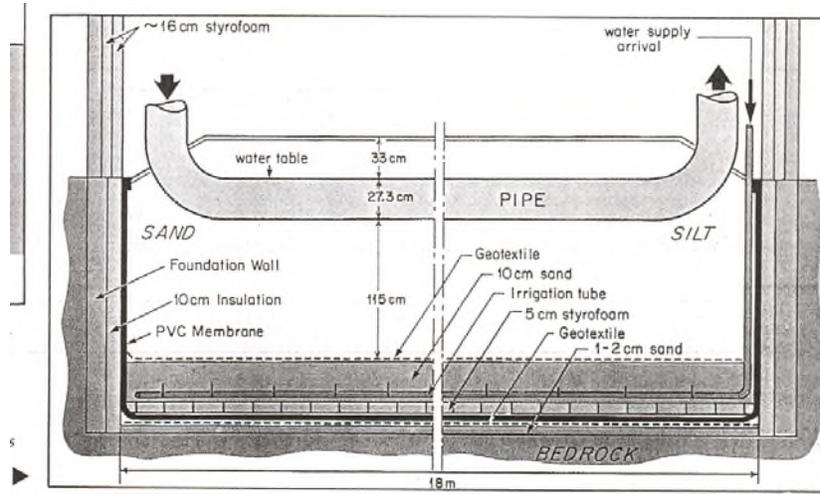


Figure 6: Longitudinal Section of pipe section at Caen, France

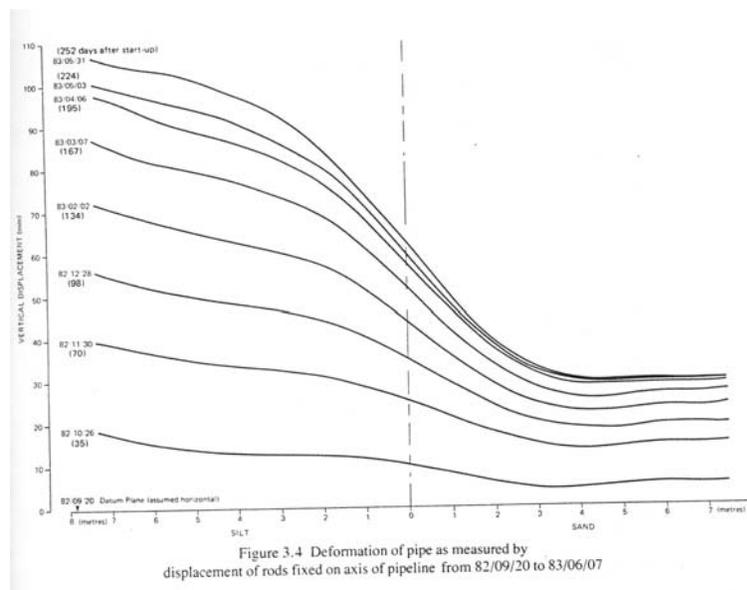


Figure 3.4 Deformation of pipe as measured by displacement of rods fixed on axis of pipeline from 82/09/20 to 83/06/07

Figure 7: Pipe movement at various times at Caen, France

An extensive series of laboratory tests for the segregation potential demonstrated the wide range of values that could be measured for identical soils as a function of sample preparation or test methodology.

**Calgary, Alberta** - These tests conclusively demonstrated that the heave rate and the total heave is significantly reduced with an increase in burial depth i.e. with increased pressure on the freezing front. A relatively small increase in pressure (i.e. burial depth) produces a large decrease in rate of heave (as shown in Figure 2). This phenomenon had been demonstrated by several researchers over a period of several decades by small-scale lab tests but had never been tested with large diameter chilled gas pipelines.

Figure 2 also shows that placing gravel under the pipe to produce a faster penetration of the freezing front and of restraining the pipe by tie downs are both effective in reducing heave rate but are of limited practicality because of cost and availability of gravel. The presence of lower clay content below the “gravel” section may have affected the resulting heave.

The use of heave rods at various depths below the pipe suggested that heaving of already frozen soil is negligible.

**Fairbanks, Alaska** - Two test sites were developed but very little is reported on the major installation, which tested a number of alternative ditch configurations and insulation as shown in Figure 8.

The second test site sponsored by the Japan Science & Technology Corporation investigated movement of a pipeline at a frozen/unfrozen interface. The pipeline heaved about 0.2m in unfrozen soil and 0.05m in the frozen soil. Although this suggests that some heave occurred in the frozen soil it was noted that the pipe settled prior to chilling with most of the settlement in the permafrost area. The permafrost would have to melt in order to settle. Hence the recorded heave may well have been due to freeze back of the thawed soil.

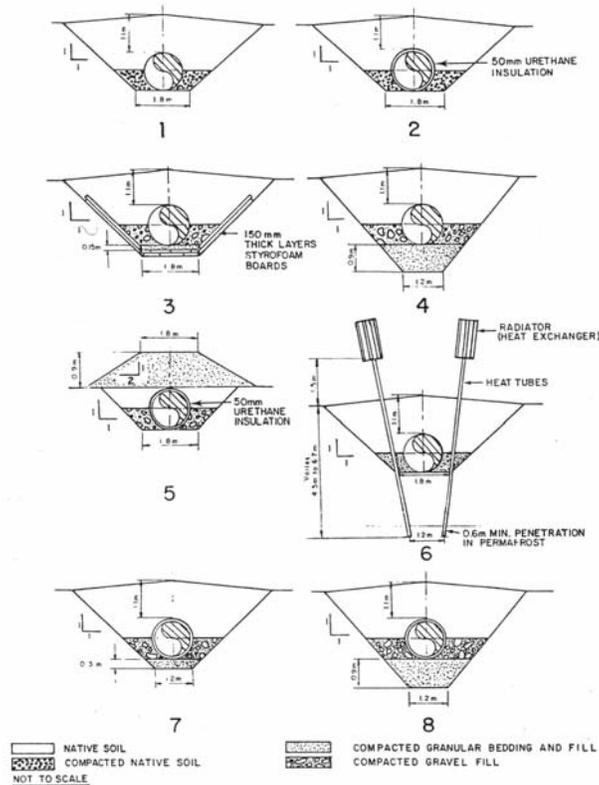


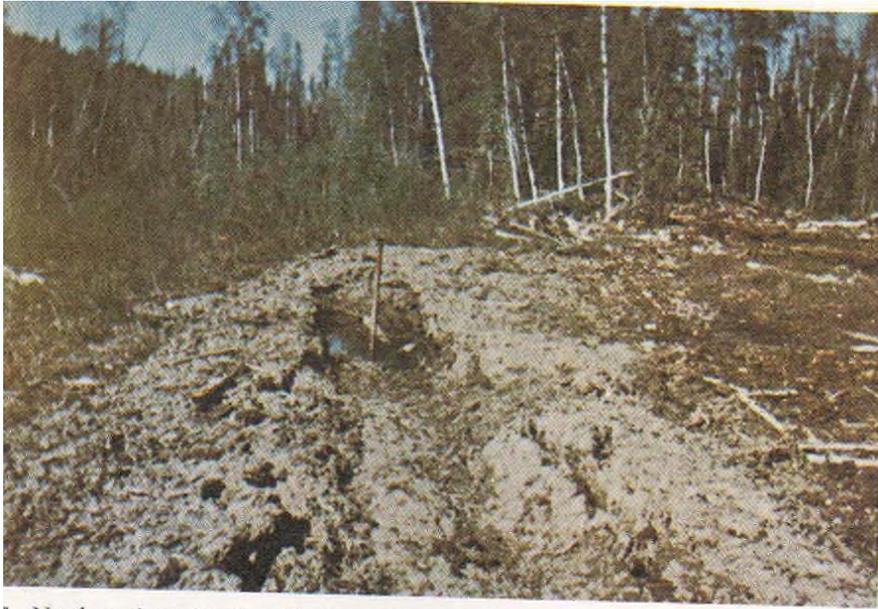
Figure 4 Ditch configurations, Fairbanks frost heave test facility

Figure 8: Test Section Configuration at 1970s Fairbanks test site

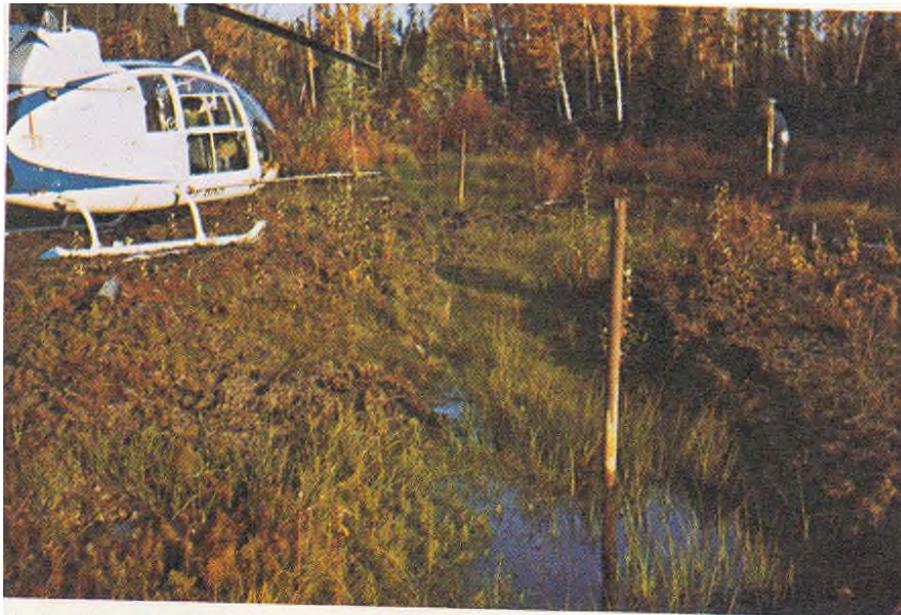
**Mountain River / Sans Sault Rapids, NWT** - The pipe section that was buried with a ditch depth of approximately 2.5m and operated fully chilled showing no significant movement over the operating period of 2 years and 3 months as shown in Figure 3. The spoil mound over the backfill remained stable. The spoil mound and ditch backfill for inactive sections and for the loops where temperature was cycled, thawed and settled extensively but was successfully re-vegetated as shown in Figure 9.

The portions of the site that were badly disturbed showed a large increase in the depth of the active layer with ponding of surface water but they were nevertheless successfully re-vegetated. Re-vegetation was carried out with native species of plants and grass where seeds were harvested and planted. Other grass types also were tested and grown successfully.

The elevated, insulated pipeline loop supported on short-drilled piles operated successfully.



7. North end of Inactive Section No. 4, August 1971. Note subsidence along ditch line.



8. Inactive Section No. 4, September 1973. View from south end showing settlement along ditch line.

Figure 9: Successful Revegetation at the Mountain River / Sans Sault Rapids Test Site

Measurements of the ground temperature around the pipe as the test proceeded show that for large diameter pipes, the thermal regime below the pipe is controlled by the pipe temperature rather than the ambient seasonal variations. Figure 10 presents temperature contours generated from thermister data for both summer and winter, showing large variations above the pipe, but very little differences below.

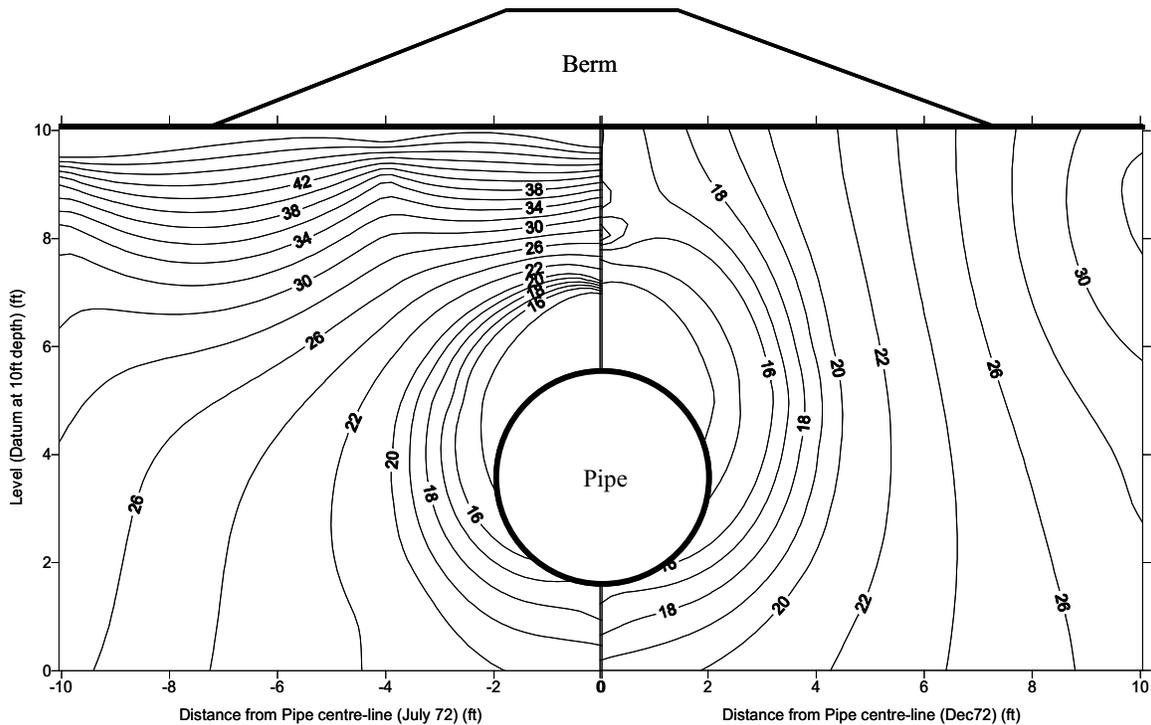


Figure 10: Temperature Contours at Sans Sault Rapids Site

**Nordegg, Alberta** - Extensive testing of soil thermal properties was carried out to provide a database for assessing a geothermal model for the prediction of thermal regime around a warm gas pipeline.

**Norman Wells, NWT** - Data on berm and half berm construction indicate very little pipeline settlement for cold gas flow. Hot gas flow produced some settlement for the pipe and berm and for the ditch section. Results are descriptive; only a few figures were found.

Active layer thickness in the test site area increased. The depth of the active layer varied according to the degree of disturbance as shown in Figure 11.

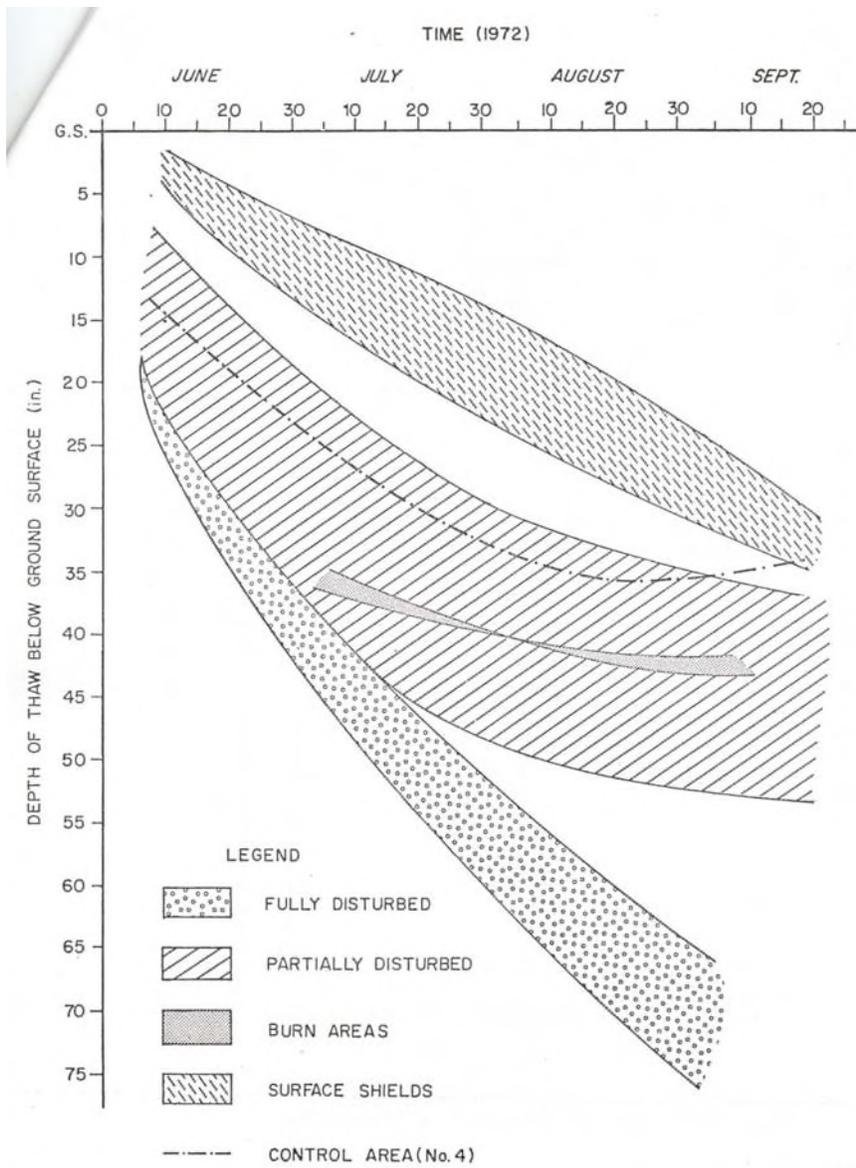


Figure 11: Increase in Active Layer Thickness at Norman Well Test Site

**Quill Creek** - Very few results published. Thaw settlement for warm gas was primary focus, testing effect of an insulated gravel pad with an uninsulated pipe in a berm, an insulated pipe in berm on an insulated pad and a concrete covered pipe on an insulated gravel pad.

Only the insulated pipe in a berm on an insulated gravel pad maintained the frozen subgrade. All others showed some subgrade thawing which would have likely continued with time. Figures 12 shows the thermal history for the different configurations.

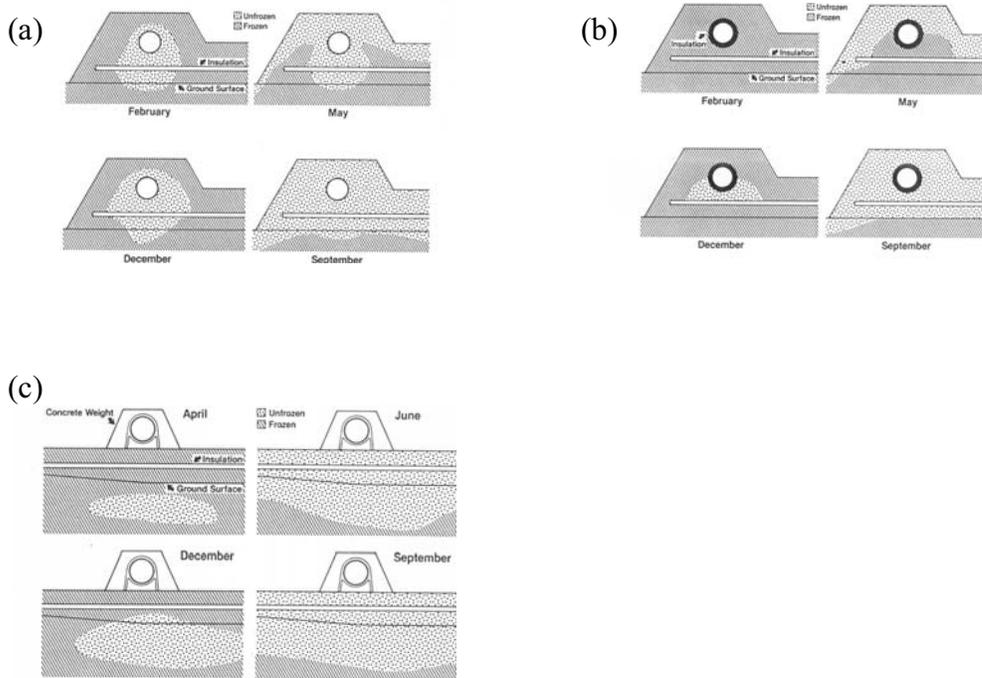


Figure 12: Thermal response for (a) uninsulated pipe in insulated embankment, (b) insulated pipe in insulated embankment, (c) concrete coated pipe on insulated gravel pad at Quill Creek Site

## 7.0 WHAT WAS LEARNED

This section sets out observations and opinions of J.I. Clark & Associates on what was learned from the test sites. It should be recognized that the records at the test sites are included in dozens of reports, many of which deal with properties of the soils, vegetation and physical and environmental setting which have been superseded by more extensive studies of the proposed route alternatives. There is no particular priority.

**Chilled Gas** - It was demonstrated that permafrost could be preserved under the pipeline and a stable trench backfill using ditch spoil could be achieved by chilling the gas to below freezing temperature. Where this appears obvious today, at that time there were no chilled gas pipelines and many questions regarding chiller reliability in northern climates, influence of climate on the ditch stability, right of way behaviour near the pipeline and so on needed to be answered. At that time, the engineering firms involved were the world leaders in technology for chilling large volumes of gas flowing under high pressure.

**Construction and Operations** - Ditching machines were modified to provide greater horsepower and better cutting teeth. The Banisher 810 was used in at Sans Sault and it was also tested extensively at other sites as well. The Henuset arctic ditcher, built to excavate permafrost, also performed very well at a number of test sites. Conventional ditchers did not fare well. Both machines still exist but company names have changed two or three times. Conventional lay in equipment where used worked well. Some of the sites used blasted ditches with cranes for setting the pipe. Backfill was stable where the gas was chilled but in ice rich soils it collapsed when the gas was warm or the pipeline was dormant. Pipe flotation was experienced in rich ice soils.

**Right of Way** - Provided that the surface was not seriously disturbed, the active layer of the right of way increased in depth but not as much as for seriously disturbed areas. It was usually measured in inches. Where the active layer was badly disturbed or stripped, water ponded and the depth of summer thaw increased several feet, for example at Sans Sault and Norman Wells. Ditch backfill eroded on sloping ground at Sans Sault Rapids. (It is understood that a slide occurred at the test site in recent years, exposing some of the pipe. No details are available. The extent to which the slide may have been related to the test site construction should be investigated.) None of the sites tested drainage and erosion control methods that were subsequently proposed for the pipeline route.

**Ditch Configuration** - Pipelines constructed in a berm or a half berm were stable except for minor slumping when the pipe was operated at above freezing temperatures. Insulation can be used to prevent sub-grade thaw. Ditches were successfully excavated by blasting and backhoe but also by ditchers adapted for frozen soil excavation. One ditcher was designed for a ten-foot depth and the other for 12 feet. Rock saws that have been tested in recent years were not available at that time.

**Frost Heave** - Most of the available information is from the Calgary test site but Fairbanks results may be available soon. The results of the Calgary test suggest that by increasing the depth of the ditch, the amount of heave can be significantly reduced to

typically be within tolerable limits. It is our opinion that a ditch depth greater than 3m would not be required and for many soil types 2m would be adequate. This opinion is based on analyses carried out for a 48" diameter pipe, operating at 1,625 psi at minus 10°C for the top grade steel available at that time.

**Thaw Settlement** - Insufficient operating time for a warm gas pipeline in permafrost prevents conclusions to be drawn. Results of a hot oil pipeline tested by MVPRL near Inuvik showed very large settlements that would be intolerable for an operating pipeline.

## 8.0 IMPORTANT ISSUES NOT STUDIED AT TEST SITES

One issue that has never been tested is the operation of a chilled gas pipeline below a river crossing. There will likely be 4 major crossings and over 200 minor crossings for a pipeline from Mackenzie Delta to Alberta. The major crossings will likely be twinned and laid in separate trenches. The pipe will likely be insulated and concrete coated. Depending upon the size of the pipe and thickness of insulation, the concrete coating may have to be quite thick to achieve the negative buoyancy required. Nevertheless, design and construction of the major crossings should not be difficult for an experienced contractor.

The minor crossings are another question. Many have over-wintering populations of fish or are spawning areas. Construction windows may be small. Directional drilling can be used for some crossings but would be impractical for all of them. Most will be trenched by backhoe or dragline and backfilled. It is likely but by no means certain that they would be insulated. Convection may prevent the formation of a large ice bulb if the pipe is not insulated but depending on the flow rate, the streambed may freeze into the water column. This could result in an icing that could be damaging to other facilities downstream and it could re-direct flow. Theoretical analysis is very difficult. A test site at a typical minor river crossing would be useful.

Design of drainage and erosion control measures on the right of way should be carefully done to ensure that the pipeline does not become exposed or that the right of way becomes unstable. The Norman Wells pipeline should provide useful experience but the challenge in continuous permafrost regions is different.

Slope stability is an issue that must receive major consideration but many problem areas can be avoided by careful routing. The slide that occurred at the Sans Sault test site should be investigated. Experience with slope stability issues and slope stabilization techniques gained from the Norman Wells pipelines should prove helpful.

## **9.0 SUMMARY AND CONCLUSIONS**

The summaries of each test site presented in the appendices of this report have been based on an extensive review of the available literature. It is acknowledged that all sources of information may not have been exhausted, but sufficient original reports have been consulted to provide the pertinent data and results. Many of the original documents relating to the test sites may have been destroyed or are “lost” within company archives, or were simply unavailable to this study due to the proprietary nature of the information.

The test facilities reviewed as part of this study provide a range of data that could be very useful to the continuing study of pipelines constructed in northern regions. The range of geometries, soil types and environmental conditions considered at the test sites covers most of the conditions expected along a transmission pipeline route from the arctic coast to southern Canada. The following comments relate to specific issues that have been addressed by the test facilities:

**Frost Heave** – The Calgary test facility provides the most comprehensive publicly available data set relating to frost heave of chilled large diameter pipelines buried in natural unfrozen soil. The four original section configurations provide data on a variety of geometries and have been extensively used to calibrate or compare analytical prediction models. In addition, the results of cold plate tests, bench scale laboratory tests, and small-scale pipeline tests were useful in understanding the behaviour of freezing soil due to operating a chilled pipeline. The Caen test facility provides data on a small diameter pipe section in well controlled and defined conditions for a series of freeze and thaw cycles. Data from this facility are also available for development and comparison with predictive tools.

**Thaw Settlement** – The test site at Inuvik provides the most comprehensive data on thaw settlement of pipelines buried in ice rich frozen ground. The Quill Creek site also provides good information on mitigative methods to overcome the effects of thaw settlement, principally using insulated gravel berms. The effect of intervals of warm (above freezing temperature) flow was investigated as part of the Caen, Sans Sault Rapids, Norman Wells and Prudhoe Bay test sites.

**Geothermal Regime** – The test sections at Caen, Calgary, Sans Sault Rapids, Norman Wells and Prudhoe Bay test sites all included extensive use of temperature sensors installed into the soil, both around the pipe and outside its zone of influence. These records provide very good data on the effects of surface and trenching activity during construction. A number of pipe sections were installed and left inactive at Mountain River, Norman Wells and Prudhoe Bay to assess the geothermal effect of delayed start-up of chilled gas operation. The temperature data is particularly useful in assessing the predictive capability of geothermal assessment tools.

**Pipe-Soil Interaction** – The data from the Caen test specifically considered the structural effect of a pipeline crossing the interface between a frost susceptible and non-susceptible soil. The pipe-soil interaction due to differential heave and restraint by the non-heaving

soil provides valuable insight into the process under such a configuration. The Sans Sault test sections were fitted with strain gauges where a pipe crossed a frozen/unfrozen interface, but they were unreliable and did not provide any useful data. The reactivated Fairbanks test site includes measurement of the effect of differential frost heave, providing additional information as the data is released.

Constructability – The test sites at Sans Sault, Norman Wells, Prudhoe Bay and Quill Creek included a number of activities related to the assessment of construction techniques and land remediation. Trenching trials which considered the potential benefits of various combinations of blasting, ditching and excavating were performed, as well as snow road and working pad construction, cathodic protection and revegetation.

Reclamation – All the field test sites were reclaimed to some extent, with revegetation and erosion control being a primary focus of the Sans Sault test site. Natural species at the site were harvested and planted in greenhouses to produce seeds that were used for extensive revegetation trials. The results were particularly successful.

## **10.0 RECOMMENDATIONS FOR FURTHER STUDY**

This study presents a brief summary of activities and findings at 10 test sites. A great deal was learned at the time and much of it remains relevant. The test sites, however, represent only a small portion of engineering studies conducted. A number of relatively small but useful and informative studies related to issues of pipeline security, safety and environmental concerns could be undertaken. Some of these are summarized below:

- Major river crossings - Six major crossings were designed and reviewed by contractors. The documentation provided for each crossing contains all of the essential information relative to the construction mode and timing, rationale for twinning, negative buoyancy considerations, cathodic protection, bank stability, location of overbends and sagbends, potential river scour, potential for ice jams and hanging ice dams. From these documents a check list for design review could be established and significant features of the major crossings could be identified for use in regulatory proceedings.
- Minor river crossings – Reports were produced setting out preliminary designs for over 200 minor river crossings. A careful review of these designs, which would not be onerous, could identify the most significant crossing with respect to construction mode and timing, icings (naturally occurring and induced), and environmentally sensitive areas. A comprehensive check list for review could be developed.
- Terrain stability – A geotechnical atlas was produced with air photos showing contours with complete terrain typing, location and logs for all boreholes, results of geophysical surveys showing frozen and unfrozen sections, slope angles etc. This atlas made up of several volumes was developed to assist with final design. Regulatory reviewers should be familiar with what is available. A brief report could

highlight areas of concern with respect to drainage and erosion control, frozen/unfrozen boundaries, slope stability, terrain sensitivity etc.

- Slope stability – The failure at Sans Sault Rapids should be reviewed and analysed in the light of previous studies undertaken: potentially unstable slopes were identified by NESL for CAGSL and reports were prepared on mitigative measures. These should be reassessed, particularly in the light of experience with the Norman Wells pipeline.
- Frost Heave – Several proprietary predictive models exist and one or two in the public domain. To the best of our knowledge, none of them take into account consolidation or plastic deformation below the frost bulb. This could be significant for soft mineral or organic soils. Rather than lifting the pipeline, growth of volume within the frost bulb and the growth of ice lenses could deform the soil below the pipe with little actual heave occurring. This has been demonstrated in centrifuge modeling of frost heave of a highly frost susceptible but soft soil. It is likely that theoretical analysis could be conducted to determine the influence of soil consistency on heave. It likely could be related to liquidity index.

All the reports for studies referenced above should be available in the public domain. CAGSL (NESL) contributed their entire library to AINA but the documents were reviewed within Esso and some very useful data reports seem to have been lost. Most design related reports were filed with the National Energy Board and should be available through CISTI or NEB. Some of the major proponents kept all their documentation, but never archived it. ASTIS and CISTI would be the best sources for this information.

**APPENDIX A**

**Caen Frost Heave Test Facility**

Test Facility	Caen Frost Heave Test Facility
Location	Caen, Normandy, France
Owner	Station de Gel, Centre de Geomorphologie
Operator	Station de Gel, Centre de Geomorphologie
Participants	Government of Canada: Energy, Mines and Resources, Canada; Natural Sciences and Engineering Research Council; National Energy Board; National Defence; and the following companies: Esso Resources Canada Limited; Foothills Pipe Lines Limited; Gulf Canada Resources; Interprovincial Pipe Line Inc.; Nova Corporation of Alberta; Shell Canada Limited; Transcanada Pipelines (Polar Gas Project); Yukon Pacific Corporation; Government of France: Laboratoire Central des Ponts et Chaussées; Centre National de la Recherche Scientifique; and Sofregaz.
Principal Researcher(s)	M. Jaime Aguirre Puente, M. Lucien Faugeres, Centre National de la Recherche Scientifique Dr. Peter Williams, Carlton University
Timing / Duration	1982 – 1993
Purpose	To undertake a full-scale experiment with precise control of the physical, thermal and hydrologic conditions. Does not model any particular field situation or pipeline foundation design.
Description of tests	Investigation of frost heave effects on a pipeline buried near the interface of frost susceptible and non-susceptible soils and frozen and unfrozen soil.
Test Components	One 273mm diameter pipe section, 18m long, buried at 33cm depth in a highly controlled and instrumented soil test bed. The pipe crossed a vertical interface between silt (frost susceptible) and sand (non-susceptible). A second set of tests was performed on a pipeline laid across a frozen / unfrozen soil interface. The soil bed was 18m long, 8m wide and 1.75m deep.
Operating Conditions	The ambient air temperature was controlled to perform freezing cycles (-0.75°C) interrupted by thaw cycles (+4°C). The pipe temperature remained at -2°C during first freeze and thaw cycle & cycled between -5°C and ambient temperature during subsequent cycles. A total of 4 freeze-thaw cycles were performed with freeze times in the range 260 to 700 days, and thaw times of 130 to 315 days.

	The second set of tests were performed with a surface temperature of $-0.75^{\circ}\text{C}$ and pipe temperature $-5$ to $-8^{\circ}\text{C}$ . A period of stress relaxation was incorporated with the pipe at $+5^{\circ}\text{C}$ prior to a further period of freezing. Freezing periods were of the order of 250 days long.
Instrumentation	Thermocouples within the soil, flux meters, surface leveling pins, tensiometers, pressure cells, heave tubes, frost depth tubes, TDR moisture content probes, pipe deflection, pipe curvature, pipe strain. Numerous laboratory cell tests also performed on soil specimens.
Summary of results	Quantification of frost penetration and soil and pipe heave and thaw settlements for freeze and thaw cycles. Calculation of stresses induced due to pipe curvature. Some evidence to challenge conventional theory relating to continued heaving of already frozen soil and orientation of ice lens formation.
Faults, problems, shortcomings	Test configuration not completely representative of expected field conditions – small diameter pipe, vertical boundary interface. Second set of tests across frozen/unfrozen interface experienced thawing of the frozen soil leading to thaw settlement.
Requirements for further work	Data has been extensively used to develop and calibrate numerical prediction geothermal and frost heave models. Invaluable data due to the highly controlled test conditions.
Reports	As listed. No final report found.
Availability / access to data	EMR reports not publicly available. Papers published in abstract form only. ASTIS & AINA call references listed (with abstract) where available.

### Reference List:

Frost Heave: Caen experiment results and some practical implications. [Atkinson, D.](#) (Student research in Canada's North : Proceedings of the Third National Student Conference on Northern Studies, Ottawa, October 23-24, 1991 / Edited by Walter O. Kupsch and James F. Basinger. Musk-ox, no. 39, special publication, 1992, p. 107) Abstract only.

ASTIS record 34117.

Languages: English and French

Libraries: ACU G600.M85 NO39 1992

Frost heave is a well studied and documented phenomenon associated with any region subjected to winters the average temperatures for which remain below freezing. This presentation provides a brief theoretical description of the processes associated with and responsible for frost heaving. It will then examine some of the results generated by an experimental facility located in Caen, France that is jointly run by Canadian and French

researchers to study the phenomena. Drawing on these results, implications for engineering concerns in the Canadian North, especially the Mackenzie Valley, will be sketched out. ...

Permafrost : large-scale research at Calgary and Caen / [Burgess, M.](#)

(Geos (Ottawa), v. 14, no. 2, Spring 1985, p. 19-22, ill., map)

ASTIS record 16454.

Languages: English

Libraries: ACU

This article details permafrost research in which the Earth Physics Branch of Energy, Mines and Resources (Canada) is involved. Experiments are underway to document the long-term effects of frost heave on buried pipelines, both insulated and non-insulated. (ASTIS)

PIPELINES AND FROST HEAVE. 1985. Proceedings of a Conference, Caen, France. Sponsored by Energy, Mines and Resources, Canada and Ministère de l'Urbanisme et du Logement, France. 75 pp. Carleton University, Ottawa, Canada. (contains following articles by project team: Experimental Observations of Differential Heaving and Thaw Settlement around a Chilled Pipeline; M.W. Smith, Soil Freezing and Frost Heaving at the Caen Experiment; S.R. Dallimore, Laboratory Characterization of Frost Heaving of Caen Silt; Dominique Blanchard and Michel Frémond, Behaviour of Soils in the Arctic; W.H. Bowes, Bending Stresses in Pipe due to Frost Heave; R.J. Kettles, Soil - Pipeline Interaction: A Review of the Problem; B. Ladanyi and G. Lemaire, Caen Pipeline Experiment: A Back-Analysis of Observations Made during the First Year of the Test.)

Experimental observations of Differential Heaving and Thaw Settlement around a Chilled Pipeline. Based on report for Earth Physics Branch, Energy, Mines & Resources, Canada, 1982.

Soil Freezing and Frost Heaving at the Caen Experiment. Smith, M. W. Geotechnical Sciences Laboratories, Carleton University.

Laboratory Characterisation of Frost Heaving of Caen Silt. Dallimore, S. R. Geotechnical Sciences Laboratories, Carleton University.

Ice Lens Formation at a Silt-Sand Interface. Smith, S.L. & Williams, P. J. Canadian Geotechnical Journal. Vol. 32. pp.488-195. 1995.

Detailed Observations on the nature of Frost heaving at a Field Scale. Smith, M.W. & Patterson, D. E. Canadian Geotechnical Journal. Vol. 26. pp.306-312. 1989.

Observations and Significance of Internal Pressures in Freezing Soil. Smith, M. W. & Onysko, D. Proceedings 5<sup>th</sup> Canadian Permafrost Conference, Laval, Quebec City. 1990.

Ice Lens Orientation around a Chilled Buried Pipe. Smith, S. L. & Williams, P. J. Proceedings 5<sup>th</sup> Canadian Permafrost Conference, Laval, Quebec City. 1990.

Geotechnical Aspects of Northern Gas Pipeline Design. Nixon, J. F., Sortland, K. A. & James, D. A. Proceedings 5<sup>th</sup> Canadian Permafrost Conference, Laval, Quebec City. 1990

The France-Canada Joint Study of Deformation of an Experimental Pipeline by Differential Frost heave. Williams, P. J., Riseborough, D. W. & Smith, M. W. Proceedings 2<sup>nd</sup> International Offshore and Polar Engineering Conference, San Francisco, USA. 1992.

Pipelines buried in freezing soil: a comparison of two ground-thermal conditions. Riseborough, D.W., P.J. Williams and M.W. Smith, 1993. Proc. of the 12th International Conference on Offshore Mechanics and Arctic Engineering Volume V: Pipeline Technology, American Society of Mechanical Engineers, Book No. G00681-1993, pp. 187-193.

Further references listed at the following website:

<http://www.freezingground.org/GSLNetwork/pipepapers.htm#RP>

<http://www.freezingground.org/GSLNetwork/france.htm>

**APPENDIX B**

**Calgary Frost Heave Test Facility**

Test Facility	Calgary Frost Heave Test Facility
Location	University of Calgary campus, NW Calgary, Alberta, Canada
Owner	Canadian Arctic Gas Study Limited (CAGSL)
Operator	CAGSL 1974-1978 Foothills 1978-1986 EMR involved since 1982
Participants	CAGSL, Foothills, Northern Engineering Services Limited (Engineering)
Principal Researcher(s)	W. A. Slusarchuk, J. I. Clark, J. F. Nixon, J. R. Elwood, L. E. Carlson
Timing / Duration	1974 – 1986
Purpose	Objectives of the full scale field buried pipeline tests: <ol style="list-style-type: none"> <li>1. Observe and monitor the performance of a 4 foot diameter pipeline buried in frost susceptible (silty) soil when operating at approximately 10°F,</li> <li>2. Determine the effect of increasing overburden pressure and replacing some of the frost susceptible soil with gravel in reducing frost heave,</li> <li>3. Obtain a better understanding and appreciation of the role of water availability in the development of frost heaving around a chilled gas pipeline, and</li> <li>4. Relate the field results to those of the laboratory frost heave and model tests in order to develop, check and redefine a predictive capacity.</li> </ol>
Description of tests	Investigation of frost heave effects on a pipeline buried in unfrozen frost susceptible soil.
Test Components	Initially 4, 12.2m long, 1.22m diameter pipe sections buried in natural frost susceptible soil. Pipe configurations where: (1) Control Section with 760mm natural backfill cover, (2) Deep Burial Section with 1675mm cover, (3) Gravel Section with 900mm gravel bedding and 760mm natural backfill cover, and (4) Restrained Section as (1) but restrained by load-controlled system. 2 pipe sections added in 1978, insulated with 15mm polyurethane covering, with similar configuration as (1) and (3) above. Berms added to control and deep burial sections in 1975.
Operating Conditions	Pipes operated at constant temperature of –10°C.
Instrumentation	Instrumentation included in-soil thermistors, heat flux transducers, heave gauges and piezometers. Comprehensive geotechnical, laboratory and small scale

	pipe test program also performed.
Summary of results	Quantification of frost penetration and soil and pipe heave for each pipe section. Observation of mitigative effects of different burial configurations. Low pore suctions generated ahead of freezing front. No observation of continued heaving of already frozen soil. Development of frost front consistent with geothermal analysis as long as water migration is considered. Frost susceptibility is sensitive to small changes in clay content. Heave generated decreases according to configuration - control, deep burial, gravel, restrained, insulated control, insulated gravel. Lower clay content in soil at gravel section may contribute to lower measured heave.
Faults, problems, shortcomings	Control section terminated in 1977 due to space requirements for building work. Berm added to control and deep burial sections hindered interpretation of long term effects.
Requirements for further work	Exceptional data available for testing and calibrating geothermal and frost heave numerical models. Generally accepted to be the most valuable and comprehensive full-scale test site undertaken to date.
Reports	As listed. No final report found.
Availability / access to data	Large collection in AINA and NEB archives. ASTIS & AINA call references listed (with abstract) where available.

### Reference List:

**Interim report on frost effects study [volume I and volume II] / [Northern Engineering Services Company](#) [Canadian Arctic Gas Study Limited](#) [Sponsor]**

Calgary, Alta. : Northern Engineering Services Co., 1975.

ASTIS record 49796.

Languages: English

Libraries: ACU TJ930.P62.I573.1975

This report describes the test facilities and laboratory equipment associated with the Frost Effects Study Program. The study program involves three phases; the field test facility, the laboratory frost heave cells and the laboratory model pipeline. In addition to the equipment description, the results from the three phases of the program collected to January 1975 are presented. The predicted and observed temperatures, heaves and pore pressure for the field test facility are presented and discussed. Results from the 4 inch frost heave cells are included, together with the data collected from the laboratory model pipeline tests. A method of predicting pipe heave is presented. The method employs the laboratory heave-pressure relationships to predict pipe heave with time. In general, good

agreement is obtained between predicted and observed heave, from penetration and pore pressures for the field test facility. The results presented in this second interim report represent part of an ongoing study, and the program of data collection and analysis is continuing. ...

**Frost heave information pursuant to National Energy Board requests of May 11, 12 and 14, 1976** / [Northern Engineering Services Company](#) [Canadian Arctic Gas Study Limited](#) [Sponsor]

Calgary, Alta. : Northern Engineering Services Co., 1976.

ASTIS record 31779.

Languages: English

Libraries: ACU TJ930.P62.F76.1976

The information contained in this report is provided in response to specific requests made by the National Energy Board during cross-examination of the Geotechnical Panel. The following information is provided: Item #1 .... Additional information on frost heave prediction procedures, and update of frost heave measurements and predictions for the four buried pipe test sections at the Calgary Test Facility. Item #2 .... Elevation measurements of riser rods on buried pipe test sections at Sans Sault Test Facility. Item #3 .... Equivalent depth of burial of Restrained Section with largest load as compared to the Deep Burial Section with present surcharge load on it. Item #4 .... Question relating to equal spacing of data points on a graph showing heave of Restrained Section plotted against frost penetration depth below pipe. The specific data points in question were those when the frost penetration depth was between 7 and 8 1/2 feet below the pipe. Item #5 .... Provide smoothed curves for plot of pipe heave against frost penetration depth below pipe for the four buried pipe test sections at the Calgary Test Facility.

**Field test results of operating a chilled, buried pipeline in unfrozen ground** / [Carlson, L.E.](#) [Ellwood, J.R.](#) [Nixon, J.F.](#) [Slusarchuk, W.A.](#)

(The Roger J.E. Brown memorial volume : proceedings of the Fourth Canadian Permafrost Conference, Calgary, Alberta, March 2-6, 1981 / Edited by H.M. French. NRCC - National Research Council of Canada, no. 20124, 1982, p. 475-480, figures)

ASTIS record 12193.

Languages: English

Libraries: ACU GB641.A2.C36 4<sup>TH</sup> 1981

In order to study the behaviour of a chilled, large-diameter pipeline buried in frost-susceptible ground, a field test facility was constructed in Calgary, Alberta. This facility, which contained four non-insulated test sections of pipe, 1.2 m in diameter, buried in frost-susceptible soil, has been operational since March 1974. Two insulated sections of pipe 1.2 m in diameter were installed in late 1978. This paper describes the layout of the test site and the geometry of the test sections. Results are presented, of the growth of the frost bulb around the pipe sections, together with the heave of the pipe sections and the soil around the pipe. The results of these full-scale frost heave field tests have aided in developing an understanding of frost heaving around a chilled pipeline. They have indicated the effects of increased overburden pressure and frost penetration rate on the rate of frost heave.

**Response to Dr. P.J. Williams' report on possible heave of chilled gas pipeline /**  
[Northern Engineering Services Company](#) [Canadian Arctic Gas Study Limited](#) [Sponsor]

Calgary, Alta. Northern Engineering Services Ltd., 1976.

38, 15 leaves : ill. ; 29 cm.

ASTIS record 31667.

Languages: English

Libraries: ACU TJ930.P62.R47 1976

Dr. P.J. Williams has restated his position with regard to frost heaving in a "Report on Possible Heave of Chilled Gas Pipeline" dated 4 February, 1976. The report was prepared in response to the rebuttal evidence presented by Drs. J.I. Clark, R.L. Harlan, P.

Hoekstra, N.R. Morgenstern and W.A. Slusarchuk on behalf of Canadian Arctic Gas Pipeline Limited before the Berger Commission on October 16, 1975. From the report it is evident that major areas of disagreements and concerns persist between Williams and CAGPL. The two major areas of disagreement are: (1) Magnitude of Shut off Pressure .... (2) Amount of Heave in Frozen Ground ....

**Interim report on frost effects study /**  
[Northern Engineering Services Company](#)  
[Canadian Arctic Gas Study Limited](#) [Sponsor]

Calgary, Alta. : Northern Engineering Services Co., 1974.

61, [89] leaves : ill. (some folded), 1 map ; 29 cm.

ASTIS record 31813.

Languages: English

Libraries: ACU TJ930.R47.NO975

The temperature of the gas in the pipeline will be chilled to below 32 degrees Fahrenheit for most of its length where it passes through areas of permafrost. In these areas where the pipeline passes through unfrozen ground the effect of freezing the ground around the pipe must be assessed. ... The frost effects study program which was developed was conveniently divided into three activities as follows: 1. Full scale field buried pipeline tests, 2. Laboratory frost heave tests, and 3. Laboratory model buried pipe tests. The overall objective of the frost effects study program was to obtain information which would assist in better defining the areas of potential frost heave along the route, the possible magnitude of the heaving problem in these areas, and the effectiveness of various remedial measures, if heaving was demonstrated to be a problem. ...

**Field test results of a chilled pipeline buried in unfrozen ground /**  
[Slusarchuk, W.A.](#) [Clark, J.I.](#) [Nixon, J.F.](#) [Morgenstern, N.R.](#) [Gaskin, P.N.](#)

In: Proceedings - International Conference on Permafrost, 3rd, Edmonton, Alberta, July 10-13, 1978. - Ottawa : National Research Council of Canada, 1978-79, v. 1, p. 877-883, ASTIS record 1952.

Languages: English

Libraries: ACU GB641 .I56 3RD 1978 V.2

... Four test sections of 1.22 m diameter gas pipeline were buried in a frost susceptible silt, and have been maintained at a temperature of -10 deg. C for about 3 years. This paper describes the instrumentation installed around the pipe sections to monitor frost penetration, frost heave and pore water pressure. Results are presented showing the

growth of the frost bulb around the pipe sections, together with heaving of the pipe and the soil around the pipe. ...

**In situ frost heave testing using cold plates** / [Nixon, J.F.](#) [Ellwood, J.R.](#) [Slusarchuk, W.A.](#)

(The Roger J.E. Brown memorial volume : proceedings of the Fourth Canadian Permafrost Conference, Calgary, Alberta, March 2-6, 1981 / Edited by H.M. French. NRCC - National Research Council of Canada, no. 20124, 1982, p. 466-474, figures) ASTIS record 12192.

Languages: English

Libraries: ACU GB641.A2.C36 4<sup>TH</sup> 1981

... The design, fabrication, installation, and instrumentation of several 0.76 m diameter cold plates are described. Instrumentation includes heave measurement rods, thermistors, and earth pressure cells. These plates have been successfully installed and operated in the south Yukon and Calgary. Results from these tests provide a bridging between small-scale laboratory testing and eventual frost heave design for large diameter, buried, chilled gas pipelines. Results from one of two cold plate installations at the pipeline research facility in Calgary are presented in detail, and brief comparisons are made with the behaviour of full-size pipeline test sections. The in situ cold plate test provides valuable test data within a few months that are a valuable aid to long-term frost heave predictions.

**Permafrost : large-scale research at Calgary and Caen** / [Burgess, M.](#)

(Geos (Ottawa), v. 14, no. 2, Spring 1985, p. 19-22, ill., map)

ASTIS record 16454.

Languages: English

Libraries: ACU

This article details permafrost research in which the Earth Physics Branch of Energy, Mines and Resources (Canada) is involved. Experiments are underway to document the long-term effects of frost heave on buried pipelines, both insulated and non-insulated. (ASTIS)

**Frost Heave and Thaw Settlement Test Facilities** / Carlson, L. E.

Pipelines and Frost heave. 1985. Proceedings of a Conference, Caen, France. Sponsored by Energy, Mines and Resources, Canada and Ministère de l'Urbanisme et du Logement, France. 75 pp. Carleton University, Ottawa, Canada.

**APPENDIX C**

**Fairbanks Frost Heave Test Facility 1**

<b>Test Facility</b>	<b>Fairbanks Frost Heave Test Facility 1</b>
Location	Chena Hot Springs Road, Fairbanks, Alaska, USA
Owner	Northwest Pipeline Company Foothills Pipelines Ltd
Operator	Northwest Pipeline Company Foothills Pipelines Ltd
Participants	Northwest Pipeline Company Foothills Pipelines Ltd Alaska International Contractors (construction) Fluor Engineers and Constructors (project management)
Principal Researcher(s)	W. A. Slusarchuk, J. R. Elwood, L. E. Carlson, D. E. Fielder
Timing / Duration	1978 -
Purpose	Objective of tests to find the right combination of burial techniques – gravel replacement, pipe insulation, shallow burial & installation of chill pipes to maintain frozen soil.
Description of tests	Investigate the performance of pipeline buried in permafrost & non-permafrost terrain.
Test Components	<p>10 test pipe sections of 1.2m diameter pipe:</p> <p>Section 1 – 120’ long bare un-insulated in native soil backfill. Used as control section.</p> <p>Section 2 – 2” urethane insulation buried on compacted and backfilled in native soil.</p> <p>Section 3 – trapezoidal trench lined with 6” foam insulating boards, bedded with compacted granular fill. Non-frost susceptible backfill.</p> <p>Section 4 – bare un-insulated, on 3’ bed of non-susceptible material.</p> <p>Section 5 – wrapped in 2” urethane insulation on compacted gravel bed. Native soil covering pipe &amp; gravel backfill.</p> <p>Section 6 – quick-freezing of adjacent soil using natural convection devices. Evaluation of mitigation of frost heave by creating total permafrost condition. Bare pipe in native soil with installation of Thermo-Tubes from Shannon Wilson of Seattle along trench. Chill tubes contain 50% methanol, 50% water.</p> <p>Section 7 – 2” urethane insulation on 1’ non-frost susceptible bedding, covered with 1’ compacted gravel &amp; backfilled with native soil.</p> <p>Section 8 – 4” urethane insulation 3’ non-frost susceptible bedding and thermo-tube installation.</p> <p>Section 9 – bare un-insulated 400’ long buried partly in</p>

	permafrost, partly in frost susceptible soil. Instrumented to indicate stress effects. West end backfilled with native soil, east end compacted gravel bedding, covered with gravel & backfilled with native soil. Section 10 – Bare uninsulated 40” long wholly in permafrost similar to Section 9 east end. The site was reactivated in 2000 with 36” diameter pipe buried in permafrost and unfrozen soil.
Operating Conditions	Pressurized to 665-675psi and chilled to 8 to 15°F.
Instrumentation	Temperature sensors in ground, heave rods, load cells to measure soil pressure exerted on the pipe, pore water pressure, heat flux transducers on pipe and in soil. Strain gauges on Section 9 pipe to detect deformity.
Summary of results	No results found in public domain.
Faults, problems, shortcomings	Unknown
Requirements for further work	
Reports	As listed.
Availability / access to data	1 trade publication article found

### References List:

Frost heave test facility: simulating, solving freeze-thaw problems for proposed gas line (Alaska construction & oil, v. 21, no. 3, Mar. 1980, p. 18-20, ill.)

(Northern development, v. 12, no. 2, Mar./Apr. 1980, p. 4-6, photos.)

Also published under title: Gas line test bed monitors frost heave, in Northern development, v.12, no.2, March/April 1980, p.4-6.

ASTIS record 4025.

Languages: English

Libraries: ACU NFSMO HC107 .A45 A43

In a seven-acre site ... near Fairbanks, pressurized, chilled air circulates through a test facility devised to determine what effects frost heaving might have on the proposed Alaska Highway gas pipeline. HC107 .A45 A43

### **Frost Heave and Thaw Settlement Test Facilities** / Carlson, L. E.

Pipelines and Frost heave. 1985. Proceedings of a Conference, Caen, France. Sponsored by Energy, Mines and Resources, Canada and Ministère de l'Urbanisme et du Logement, France. 75 pp. Carleton University, Ottawa, Canada.

**APPENDIX D**

**Fairbanks Frost Heave Test Facility 2**

<b>Test Facility</b>	<b>Fairbanks Frost Heave Test Facility 2</b>
Location	Chena Hot Springs Road, Fairbanks, Alaska, USA (Site of old Northwest & Foothills Pipelines test facility)
Owner	Japan Science and Technology Agency
Operator	Japan Science and Technology Agency
Participants	Japan Science and Technology Agency University of Alaska, Fairbanks Hokkaido University, Japan AMEC Earth & Environmental
Principal Researcher(s)	S. L. Huang, S. Akagawa, J. Oswell
Timing / Duration	1999 -
Purpose	Objectives are: (1) Investigate the thermal influence of the pipeline and the resulting thermal characteristics developed along the pipeline in response to the operation of the chilled pipeline, (2) Study the frost heave characteristics of the pipeline resulting from differential heave across the permafrost-thawed soil transition. Frost heave aspects that are investigated include foundation heave, overburden, heave characteristics and pipeline movement.
Description of tests	Investigate the thermal influence and performance of a pipeline buried across an interface of shallow and deep permafrost.
Test Components	One test pipe section, 105m long, 0.9m diameter, 8.5mm wall thickness, X65 grade steel. 0.9m cover to top of pipe. Trench backfilled using dry sand to pipe crown topped with crushed insitu soil to the surface. 30m length of pipe placed in shallow permafrost (2-3m depth), 75m in unfrozen ground (deep permafrost at 7-8m depth).
Operating Conditions	Nominal pipe operating temperature $-10^{\circ}\text{C}$ , with approximately $2^{\circ}\text{C}$ temperature rise between inlet and outlet.
Instrumentation	3 thermister fences placed along the length of the pipe from 1 to 6m from pipe axis and to 8m depth. Permafrost temperature $-0.08$ to $-0.25^{\circ}\text{C}$ indicating unstable slowly degrading permafrost regime. Instrumentation included 150 thermisters, 40 strain gauges at 11 locations along pipeline, 28 heave rods welded to top of pipe, 5 heave gauges below pipeline, several other types of soil settlement devices.

Summary of results	3 years of thermal data available on the temperature regime below and around the pipe. Pipeline movement measured using heave rods. Pipe showed initial settlement prior to chilling, with higher values in permafrost – effect of construction disturbance. Maximum absolute pipeline heave over 3 years of chilling was 0.197m in unfrozen soil, 0.049m in frozen soil.
Faults, problems, shortcomings	Non reported
Requirements for further work	It is understood that further data will be published in the near future.
Reports	As listed.
Availability / access to data	It is understood that further data will be published in the near future.

### Reference List:

Field Investigation of Soil Heave by a Large Diameter Chilled Gas Pipeline Experiment, Fairbanks, Alaska. Huanh, S. L., Bray, M. T., Akagawa, S. & Fukuda, M. ASCE Journal of Cold Regions Engineering, Vol 18, No. 1, pp. 2-34, March 2004.

**APPENDIX E**

**Inuvik Hot Oil Line Test Facility**

Test Facility	Inuvik Hot Oil Line Test Facility
Location	2 miles north of Inuvik, NWT, 3000' east of Mackenzie River
Owner	Mackenzie Valley Pipe Line Research Limited
Operator	Canadian Bechtel Limited contracted to construct and operate the facility
Participants	Atlantic Richfield Canada Limited, BP Oil Limited, Elf Oil Exploration and Production Canada Limited, Gulf Oil Canada Limited, Hudson's Bay Oil and Gas Company Limited, Imperial Oil Limited, Interprovincial Pipeline Company, Shell Canada Limited, Standard Oil Company of British Columbia Limited, Texaco Exploration Company, Trans Canada Pipe Lines Limited, Transmountain Oil Pipeline Company, Valvoline Oil Company of Canada Limited.
Principal Researcher(s)	Rowley, G. Watson, W. Slusarchuk (NRC)
Timing / Duration	1969 - 1972
Purpose	Primary objective was to study the technological and economic feasibility of constructing a 48" diameter crude oil pipeline from the north slope of Alaska through the Yukon and Northwest Territories to Edmonton, Alberta. Specifically related to the transport of warm oil in permafrost zones.
Description of tests	Evaluate insulating methods regarding heat radiation during operation & oil cooling during shutdown, feasibility of start-up after shutdown, stresses generated by pipeline expansion due to heat, vibration frequencies and amplitudes of elevated pipeline under wind and operating conditions, movement of pipe loop during operation.
Test Components	2000' long experimental closed loop test section, 48" diameter. 3 methods of construction – pipe supported on pile bents, pipe covered by berm and pipe buried in permafrost. Half of the loop was straight with pipe constructed in a gravel berm or gravel a pad 2-5' thick. The return section was supported above ground on 16" wooden piles following a zig-zag pattern with three 12 & two 6 degree bends in 1000' length to allow thermal expansion. Piles installed in 20" holes to 16' depth. Pipe allowed to slide over Teflon coated supports. Pile supports 70' apart. Insulation coating tested in buried & above ground sections – polyurethane 2 & 4" thick & Polyken tape wrapped, Lexan General Electric, 2" thick,

	Styrofoam Bolster Blocks & Polyurethane foam with polyethelene jacket. Also a 4" diameter insulated pipe buried at 2' depth to investigate direct contact with warm permafrost. Insulation was 2" polyurethane foam with polyethylene jacket.
Operating Conditions	Operated by pumping warm oil through system. Temperature gradually increased to max 160°F, with cooling tests at intervals, with both winter and summer testing.
Instrumentation	Temperature probes inserted into the pipe and to 10' depth in the soil below and adjacent to the pipe. Strain gauges attached to the surface of the pipe at points of expected maximum stress. Accelerometer sensors to record wind induced vibrations in the above ground section. Longitudinal and transverse movement rods welded to the pipeline for survey. Probing of the active layer to measure permafrost degradation during summer.
Summary of results	Reports listed on ASTIS suggesting that comprehensive data is available on the effect of warm pipelines on permafrost degradation.
Faults, problems, shortcomings	
Requirements for further work	
Reports	Numerous reports listed on ASTIS database, but not found at AINA.
Availability / access to data	

### Reference List:

Feasibility study, 1972 : back-up data : volume 18 : Geotechnical studies, pipeline construction, stations & terminals, communications, operations & maintenance / [Mackenzie Valley Pipe Line Research Limited](#)

Calgary, Alta. : Mackenzie Valley Pipe Line Research Limited, 1972.

1 v. (various pagings) : ill., maps ; 30 cm.

ASTIS record 31989.

Languages: English

Libraries: ACU TJ930 .R47 NO.266

[This document consists of several different reports with different corporate and personal authors. The titles and authors of these reports are as follows:] 18-1 Effects of ground ice variability and resulting thaw settlement on buried warm-oil pipelines, Speer, T.L., Watson, G.H., and Rowley, R.K., 1972. 18-2) Texaco permafrost density logging report, O'Connell, L.P., and Freeborn, W.D., Texaco Exploration Canada Ltd., 1972. 18-3) Interim report, Thermal conductivity measurements of frozen and thawed permafrost from the Inuvik areas, Slusarchuk, W.A., MVPLRL, 1972. 18-4) Final report, Thermal

conductivity measurements of frozen and thawed permafrost from the Inuvik area, Slusarchuk, W.A., MVPLRL, 1972. 18-5) Gathering, handling and preparing permafrost samples for thermal conductivity measurements in Inuvik, N.W.T., Greebe, F., MVPLRL, Spring 1972. 18-6) Thermal conductivity measurements in Inuvik and Ottawa, Greebe, F., MVPLRL, 1972. 18-7) A computer based system for borehole file maintenance and generalized retrieval, Crandlemire, G.W., Computer Sciences Canada Ltd., 1972. 18-8) Investigation of a Mackenzie River crossing near Sans Sault Rapids, Watson, G.H., MVPLRL, 1972. 18-9) Site investigation for insulated road experimental section near Inuvik, N.W.T., Watson, G.H., MVPLRL, 1972. 18-10) Vertical and lateral pile load tests in permafrost, Rowley, R.K., Watson, G.H., and Ladanyi, B., MVPLRL, 1972. 18-11) Results of pressuremeter tests at the Inuvik test site, Ladanyi, B., MVPLRL, 1972. 18-12) Design of laterally loaded piles in permafrost, Ladanyi, B., MVPLRL, 1972. 18-13) Performance of a warm oil pipeline buried in permafrost, Watson, G.H., Rowley, R.K., Slusarchuk, W.A., MVPLRL, 1972. 18-14) Performance of a 48-inch warm oil pipeline supported on permafrost, Rowley, R.K., Watson, G.H., Wilson, T.M., Auld, R.G., MVPLRL, 1972. 18-15) Instrumentation around a warm oil pipeline buried in permafrost, Slusarchuk, W.A., Watson, G.H., Speer, T.L., MVPLRL, 1972. 18-16) Determination of some frozen and thawed properties of permafrost soils, Watson, G.H., Rowley, R.K., & Slusarchuk, W.A., MVPLRL, 1972. 18-17) Pile installation evaluation and load testing program at Dawson City, Yukon Territory, for Becker Drills Limited, Winn, R.H., Rogers, G.W., Dames & Moore, 1972. 18-18) Interim report on frozen core testing, Civil Engineering Department, University of Saskatchewan, 1972. 18-19) Settlement analysis of Inuvik uninsulated berm section, Rowley, R.K., and Watson, G.H., MVPLRL, 1972. 18-20) Simulation of surface energy exchange, Skjolingstad, L., MVPLRL, 1972. 18-21) Automatic temperature recording and data storage system, Skjolingstad, L., MVPLRL, 1972. 18-22) Data summary, Inuvik test facility, Skjolingstad, L., MVPLRL, 1972. 18-23) Thermal simulator studies, Skjolingstad, L., MVPLRL, 1972. 18-24) Construction cost development economic comparisons of Prudhoe Bay to Edmonton versus Tuktoyaktuk to Edmonton, Schroeder, W.W., MVPLRL, 1972. 18-25) Construction cost development Tuktoyaktuk to Edmonton, Schroeder, W.W., MVPLRL, 1972. 18-26) Stations and terminals annual capital investment schedule, Stamberg, J.C., MVPLRL, 1972. Communications annual capital investment schedule, Stamberg, J.C., MVPLRL, 1972. Annual operating and maintenance cost schedule, Stamberg, J.C., MVPLRL, 1972.

Feasibility study : 1971 : back-up data : volume 6 - below ground design / [Mackenzie Valley Pipe Line Research Limited](#)

Calgary, Alta. : Mackenzie Valley Pipe Line Research Limited, 1971.

1 v. (various pagings) : ill., maps ; 30 cm.

ASTIS record 31975.

Languages: English

Libraries: ACU TJ930 .R47 NO.414

[This document consists of several different reports with different corporate and personal authors. The titles and authors of these reports are as follows:] 3-1) Preliminary report, underground pipe line in permafrost test facility, Moreau, B.L., Williams Brothers

Canada Limited, May 25, 1971. 3-2) Belowground design study, Hochstein, S.L., Sanders, M.D., and White, C.H., Continental Pipe Line Company, December, 1971.

Feasibility study : 1971 : back-up data : volume 5 - above ground design / [Mackenzie Valley Pipe Line Research Limited](#)

Calgary, Alta. : Mackenzie Valley Pipe Line Research Limited, 1971.

ca. 500 leaves : ill. ; 30 cm.

Contains : Inuvik 48-inch loop, August 15, 1970 - January 2, 1972 : Final report.

ASTIS record 31974.

Languages: English

Libraries: ACU

Two above-ground construction techniques were used for the 2,000-foot long, 48-inch diameter test loop at Inuvik, N.W.T. This report evaluates the thermal and mechanical performance of these techniques, describes the test facilities and summarizes the operating history. Pipe movement and corresponding induced stresses are analyzed with the aid of survey data obtained throughout the test period. Pile movement is similarly assessed. Thermal data obtained included ambient, air temperature, surface and sub-surface ground temperature, oil and insulation temperatures, weather data and soil thermal conductivities. A discussion of temperature measuring systems is provided. The capability of a simulator model to compute thermal performance in permafrost systems is studied in some detail by comparing observed and computed temperatures. Data on depth of thaw and settlement of the insulated and uninsulated pipe in the berm are presented and discussed.

Feasibility study : 1971 : back-up data : volume 4 - above ground design / [Mackenzie Valley Pipe Line Research Limited](#)

Calgary, Alta. : Mackenzie Valley Pipe Line Research Limited, 1971.

1 v. (various pagings) : ill., maps, plans ; 30 cm.

ASTIS record 31973.

Languages: English

Libraries: ACU

[This document consists of several different reports with different corporate and personal authors. The titles and authors of these reports are as follows:] 2-1) Design concepts report, Termina, J.J., Cities Service Oil Company, September, 1971. 2-2) Design criteria report, termina, J.J., Cities Service Oil Company, December, 1971. 2-3) Analysis of above-ground, zig-zag configuration, Termina, J.J., Cities Service Oil Company, March, 1972. 2-4) Stress criteria report, Walker, G.E., Shell Pipe Line Corporation, October 8, 1971. 2-5) Allowable stress criteria - moment-curvature relationship, Walker, G.E., Shell Pipe Line Corporation, March 13, 1972. 2-6) Inuvik pipe curvature and settlement report, Walker, G.E., Shell Pipe Line Corporation, December 30, 1971. 2-7) Terrain typing for Inuvik test site, Mollard, J.D., J.D. Mollard and Associates Limited, January, 1972. 2-8) Inuvik soil tests summary, Watson, G.H., Mackenzie Valley Pipe Line Research Limited, March, 1972. 2-9) Inuvik berm pipe support conditions, Speer, T.L., and Watson, G.H., Mackenzie Valley Pipe Line Research Limited, September, 1971. 2-10) Inuvik pile load tests, Watson, G.H., and Rowley, R.K., Mackenzie Valley Pipe Line Research Limited, March, 1972. 2-11) Soil and permafrost data report-Inuvik above ground test loop,

Fujino, T.J., Ripley, Klohn & Leonoff Alberta Ltd., January 11, 1971. 2-12) Survey data report-Inuvik above ground test loop, Harper, T.R., Ripley, Klohn and Leonoff Alberta Ltd., January 8, 1971.

Research at Inuvik. Mackenzie Valley Pipe Line Research Limited. 1970. TJ930.  
P62.M32.1970 C.1

**APPENDIX F**

**Mountain River / Sans Sault Rapids Frost Heave Test Facility**

<b>Test Facility</b>	<b>Mountain River / Sans Sault Rapids Frost Heave Test Facility</b>
Location	Located on the west bank of the Mackenzie River, at the confluence of Mountain & Mackenzie Rivers just upstream of Sans Sault Rapids, 65 miles NW of Norman Wells, NWT.
Owner	Northwest Project Group (NPG) Canadian Arctic Gas Study Limited (CAGSL) from 1972
Operator	1970-1973
Participants	NPG CAGSL Northern Engineering Services Limited (Engineering)
Principal Researcher(s)	L. G. Williams (construction & operation), D. Dabbs (Research), Hardy Associates (Geotechnical)
Timing / Duration	1970 – 1973
Purpose	<p>Purpose of the Arctic Test Facility:</p> <ol style="list-style-type: none"> <li>1. To demonstrate the feasibility of the chilled gas pipeline design. To show that with appropriate design, reasonable construction care and proper revegetation techniques, natural gas pipelines can be constructed and operated safely in high ice content permafrost without adverse effect to the environment.</li> <li>2. To provide a means of field verification of computer programs, designed to predict changes both in flowing gas temperatures and soil temperatures around the pipeline.</li> <li>3. To provide a means of studying methods of maintaining the stability of the pipe, backfill and right-of-way (including revegetation techniques) after disturbance by pipeline construction. It was recognized that such measures were most important between time of construction and time of operation of the chilled gas pipeline.</li> <li>4. To determine suitable operating and testing procedures</li> <li>5. To better understand northern construction problems with respect to construction techniques, weather, transportation, logistics and communication.</li> </ol>
Description of tests	Pipeline buried in ice rich permafrost, chilled operation with periods of warmer gas. Also investigation of the effect of inactive sections to simulate delays in chilled operation. Winter road construction, piled foundations and excavation methods also evaluated.
Test Components	2 pipe loops – buried cold loop & cycling loop, 48” diameter pipe interconnected with 16” above ground

	<p>pipe. One section supported above ground on piles with the other sections buried at 8' to bottom of the pipe. Trenches approx. 5' wide, 8' deep. 7 inactive sections also installed, 42" diameter, 80' long, except one section 48" diameter, 16' long. All buried to 8' average in variety of topography:</p> <p>Section 1 thermocarst area, flat poorly drained, wet, test for floatation.</p> <p>Section 2 sloping bank of Mountain River, 15-16 deg, test for instability of north facing bank. Vertical ice lenses signify recent slope movement.</p> <p>Section 3 across seasonally flowing creek, reasonable flow during spring run off, test for flotation and erosion problems.</p> <p>Section 4 low lying poorly drained.</p> <p>Section 5 low lying semi muskeg zone.</p> <p>Section 6 east facing slope of Mackenzie River 8-10 deg slope test for instability.</p> <p>Section 7 adjacent to active section 2 (cold loop) where organic peat is 8-10' thick.</p>
Operating Conditions	<p>Cold loop: 3, 500' sections operated at 20 to 25°F, reduced to 5 to 7°F after 1 year. Cycling loop: 2, 500' sections operated at 25°F with short warmer periods at 44°F.</p>
Instrumentation	<p>Silicon diode sensors with copper constantan thermocouples used to check accuracy of the primary system, thermocouples installed in ditching test areas and vicinity of inactive sections, strain gauges to monitor structural response of cold and cycling loops and riser rods used for surveying pipe movement.</p>
Summary of results	<p>The ground next to the cold loop pipe did not thaw during summer and the depth of the active layer was less than at inactive pipes, but was present. Thawing of the permafrost at the cycling loop occurred within a few hours of warming the air above freezing, most rapidly in summer. Water could not escape from ice rich backfill and the pipes became buoyant and showed some upward movement. Geothermal predictions were verified successfully against test sections. Very little or no pipe movement recorded generally. The inactive sections allowed the active layer to extend to below the top of pipe at the end of summer, in some cases to below the buried pipe.</p>
Faults, problems, shortcomings	<p>Strain gauges were sensitive to atmospheric humidity and led to large errors – no attempts to correlate observed stresses with pressure, temperature or pipe movement.</p>

Requirements for further work	Useful data on construction operations and stability of pipes installed in permafrost. Limited data on frost heave or thaw settlement. Also invaluable data relating to practical aspects of pipeline construction and effects of delayed operational start-up. Extensive revegetation studies providing valuable demonstration of construction and operation effects in ice rich permafrost.
Reports	As listed.
Availability / access to data	ASTIS & AINA call references listed (with abstract) where available.

### Reference List:

Final report : Arctic Test Facility, Sans Sault, N.W.T. : volume 1 - general, December 1973 / [Northern Engineering Services Company](#) [Canadian Arctic Gas Study Limited](#) [Sponsor]

Calgary, Alta. : Northern Engineering Services Co., 1973.

[69] leaves ; 28 cm.

ASTIS record 31828.

Languages: English

Libraries: ACU TJ930 .R47 NO.989

... The overall objective of the Arctic Test Facility was to provide information necessary for the development of engineering design, construction and operation procedures for a safe and reliable pipeline through permafrost areas, which would have a minimal effect on the natural environment. With respect to the pipeline, information was required re: Leaving the pipe inactive for one or more seasons prior to going into operation, operation of a chilled gas line in permafrost areas, and the problems which may arise from operating for short periods at temperatures above 32 degrees Fahrenheit. Additional information was also desired with respect to the design, construction and long term performance of structure foundations, and the effects of disturbance on the permafrost terrain. The facility needed to be large enough to obtain information relative to the logistics of supplying men, equipment and materials to the site, and to the actual construction methods such as clearing, ditching, pipe laying, backfilling and the restoration of disturbed areas. The problems associated with the construction of temporary winter access roads also needed to be evaluated. ..

General report, Arctic Test Facility, Sans Sault, N.W.T. : draft / [Northern Engineering Services Company](#) [Canadian Arctic Gas Study Limited](#) [Sponsor]

Calgary, Alta. : Northern Engineering Services Co., 1974.

50, [33] leaves : ill. (some col.), maps ; 29 cm.

Contains 20 folded illustrations.

ASTIS record 31829.

Languages: English

Libraries: ACU TJ930 .R47 NO.988

... This report discusses the Sans Sault Test Facility which was constructed during the winter of 1970-71 and operated continuously to January, 1973. The research programs carried out during the construction and operation phases of the Test Facility related to construction practices, the change in ground thermal regime around buried operating and inactive or dormant pipes, the geotechnical behaviour of the permafrost and related behaviour of the pipe, the revegetation of disturbed areas, and the cathodic protection of the pipe in permafrost. On the basis of the results of the studies undertaken at the Test Facility, it is considered that the feasibility of a chilled gas pipeline design has been demonstrated, i.e., with appropriate design, reasonable construction care and proper revegetation techniques, natural gas pipelines can be constructed and operated safely at temperatures below 32 degrees F in permafrost terrain without adverse effect to the environment.

Report on geothermal and meteorological studies, Arctic Test Facility, Sans Sault, N.W.T. / [Northern Engineering Services Company](#) [Canadian Arctic Gas Study Limited](#) [Sponsor]

Calgary, Alta. : Northern Engineering Services Co., 1974.

ix, 60, [121] leaves : ill. (some folded), 1 map ; 29 cm.

Mostly graphs.

ASTIS record 31830.

Languages: English

Libraries: ACU TJ930 .R47 NO.987

This report deals with the geothermal and meteorological studies undertaken at the Sans Sault Test Facility, N.W.T. Initial field reconnaissance for site selection was undertaken during June and July, 1970, construction began that fall, the Facility became fully operational in March, 1971, and data collection ended in January, 1973. ... The major studies at the Facility were undertaken at a cold loop and a cycling loop. ... Ground temperatures were measured around the buried pipe sections. These temperatures were used in the geothermal computer program verification studies by comparing measured and predicted temperatures. The measured temperatures were also used to establish the depth of the active layer over the pipe and in the adjacent right-of-way at various times of the year. Active layer studies were undertaken at the buried pipeline sections, under gravel pads, and in disturbed and undisturbed areas. In these studies the temperature and depth of the active layer was measured. Cold winter ambient air was circulated with a blower through a group of pipe piles placed in permafrost. Ground temperatures were measured around these ventilated piles and around an adjacent non-ventilated control pile. Temperatures inside other pipe piles under buildings were also measured. The amount of heat flowing into or out of the ground was measured at several sites associated with the revegetation studies. ... The meteorological studies carried out consisted of measuring several meteorological parameters such as maximum and minimum daily air temperatures, wind speed and direction, snow cover, sunshine, barometric pressure and relative humidity.

**Frost heave information pursuant to National Energy Board requests of May 11, 12 and 14, 1976** / [Northern Engineering Services Company](#) [Canadian Arctic Gas Study Limited](#) [Sponsor]

Calgary, Alta. : Northern Engineering Services Co., 1976.

ASTIS record 31779.

Languages: English

Libraries: ACU TJ930.P62.F76.1976

The information contained in this report is provided in response to specific requests made by the National Energy Board during cross-examination of the Geotechnical Panel. The following information is provided: Item #1 .... Additional information on frost heave prediction procedures, and update of frost heave measurements and predictions for the four buried pipe test sections at the Calgary Test Facility. Item #2 .... Elevation measurements of riser rods on buried pipe test sections at Sans Sault Test Facility. Item #3 .... Equivalent depth of burial of Restrained Section with largest load as compared to the Deep Burial Section with present surcharge load on it. Item #4 .... Question relating to equal spacing of data points on a graph showing heave of Restrained Section plotted against frost penetration depth below pipe. The specific data points in question were those when the frost penetration depth was between 7 and 8 1/2 feet below the pipe. Item #5 .... Provide smoothed curves for plot of pipe heave against frost penetration depth below pipe for the four buried pipe test sections at the Calgary Test Facility.

Mountain River test site : recommended methods and procedures for terrain investigation and testing / [R.M. Hardy and Associates](#)

Edmonton, Alta. : R.M. Hardy & Assoc., 1970.

14, [7] leaves : 1 map ; 30 cm.

ASTIS record 31801.

Languages: English

Libraries: ACU TJ930 .R47 NO.957

The object of installing inactive pipe sections is to assess the consequences of leaving a backfilled trench for one or two summers without any chilled gas being put through the pipe. We should attempt to find out under what conditions we can lay inactive pipe without fear of severe right-of-way degradation or pipe distress and, at the other extreme, what conditions of terrain should be avoided at all cost. In between these two extremes are conditions where an inactive pipe may be left for some time but certain precautions during construction will be required, particularly as regards the backfilling. There are 500 feet of 42 inch diameter steel pipe at the test site intended to be used in inactive sections. ... The desired results can best be achieved by attempting to obtain a maximum variation in: soil types, ground ice conditions, topography and previous land use. Some variation in the native vegetation is also desirable.

Additional soil testing arctic test facility, Mountain River, N.W.T. / [R.M. Hardy and Associates](#) [Williams Brothers Canada Limited](#) [Sponsor]

Edmonton, Alta. : R.M. Hardy and Assoc., 1972.

13, 3 leaves, [115] leaves of plates : col. ill. ; 29 cm.

Mostly tables and graphs.

ASTIS record 31812.

Languages: English

Libraries: ACU TJ930 .R47 NO.984 V.1

R.M. Hardy and Associates Ltd. has been authorized by Williams Brothers Canada Ltd. to undertake a limited program of additional testing on selected soil samples from the vicinity of the Arctic Test Facility, Mountain River, N.W.T. This report is intended to be an Addendum to our report "Subsurface Conditions, Active and Inactive Test Sections, Arctic Test Facility, Mountain River, N.W.T." August 31, 1971. In addition, one soil sample from Test Hole 633 (located in the Ox-bow Lake) was also tested in this program.

Northwest Project Mountain River test site : cold & cycling loops, sections 1,2,3 & 4 test hole logs / [R.M. Hardy and Associates](#) [Northwest Project Study Group](#) [Sponsor]

Edmonton, Alta. : R.M. Hardy and Assoc., 1971.

[2] leaves, [228] leaves of plates : ill., 1 map ; 29 cm.

ASTIS record 31804.

Languages: English

Libraries: ACU TJ930 .R47 NO.954

This report consists of 228 tables which describe soil conditions and analyses of the Northwest Project Mountain River test site; both laboratory data and field data are described. (ASTIS)

Soil and permafrost conditions, Mountain River test site, N.W.T., E-1928, July 24, 1970

/ [R.M. Hardy and Associates](#) [Williams Brothers Canada Limited](#) [Sponsor]

Edmonton, Alta. : R.M. Hardy & Assoc., 1970.

ca. 150 leaves : ill., maps ; 29 cm.

Appendix D : Preliminary botanical report - Sans Sault Rapids test area by R.G.H. Cormack.

ASTIS record 31800.

Languages: English

Libraries: ACU

... R.M. Hardy & Associates Ltd. undertook an investigation of a proposed test site situated at the confluence of the Mackenzie and Mountain Rivers, Northwest Territories. It is planned to use the site to install a pipeline test facility in order that the construction and operation of a large diameter natural gas pipeline in permafrost areas can be studied over a period of time. ... Briefly, the conditions desired at the test site are: a wide variety of soil and ground ice conditions, some organic terrain, a water course that could be blocked or dammed, exposures of subsoil along rivers or creeks, "thermokarst" lakes or ponds, a source of dry borrow material (including gravel), a good barge off-loading site. Some recently cleared seismic lines, reasonable assessibility to scheduled air and water transportation.

Mountain River test site : recommended methods and procedures for terrain investigation and testing / [R.M. Hardy and Associates](#)

Edmonton, Alta. : R.M. Hardy & Assoc., 1970.

14, [7] leaves : 1 map ; 30 cm.

ASTIS record 31801.

Languages: English

Libraries: ACU TJ930 .R47 NO.957

The object of installing inactive pipe sections is to assess the consequences of leaving a backfilled trench for one or two summers without any chilled gas being put through the pipe. We should attempt to find out under what conditions we can lay inactive pipe without fear of severe right-of-way degradation or pipe distress and, at the other extreme, what conditions of terrain should be avoided at all cost. In between these two extremes are conditions where an inactive pipe may be left for some time but certain precautions during construction will be required, particularly as regards the backfilling. There are 500 feet of 42 inch diameter steel pipe at the test site intended to be used in inactive sections. ... The desired results can best be achieved by attempting to obtain a maximum variation in: soil types, ground ice conditions, topography and previous land use. Some variation in the native vegetation is also desirable.

Mountain River field logs, March 1971, E-1928 / [R.M. Hardy and Associates](#)  
[Northwest Project Study Group](#) [Sponsor]

Edmonton, Alta. : R.M. Hardy and Assoc., 1971.  
ca. 300 leaves : ill. ; 29 cm.

ASTIS record 31805.

Languages: English

Libraries: ACU TJ930 .R47 NO.945

These field logs document the findings of test holes drilled at the Mountain River site. It contains both laboratory data and field data soil descriptions. (ASTIS)

Soil conditions : trenching test areas, Mountain River site, E-1928-8 / [R.M. Hardy and Associates](#) [Northwest Project Study Group](#) [Sponsor]

Edmonton, Alta. : R.M. Hardy and Assoc., 1971.

9, 4, 4 leaves, 15 leaves of plates : ill., 1 map ; 28 cm.

ASTIS record 31806.

Languages: English

Libraries: ACU TJ930 .R47 NO.947

This report describes the soil conditions at three areas selected for trenching tests, carried out during March of 1971, in the vicinity of the Arctic Test Facility at Mountain River. A preliminary report, in letter form, was sent to Williams Brothers Canada Limited on April 14, 1971. The locations of the three test areas are shown ....

Report on terrain investigations, arctic test facility, Mountain River, N.W.T., E-1928-2 / [R.M. Hardy and Associates](#) [Northwest Project Study Group](#) [Sponsor]

Edmonton, Alta. : R.M. Hardy and Assoc., 1971.

1 v. (various pagings) : ill. (some col.), maps ; 29 cm.

Re-draft of June 7, 1971.

Six folded illustrations attached.

ASTIS record 31807.

Languages: English

Libraries: ACU TJ930 .R47 NO.984 V.1

This report covers the work done in the field and in the laboratory by R.M. Hardy & Associates Ltd. for the Arctic Test Facility, Mountain River, N.W.T., during the period

November 11, 1970 to January 31, 1971. A further report will be issued to cover the work carried out during March, 1971. ... After a decision had been made to proceed with the construction of the Arctic Test Facility at this site, a soil and terrain investigation was planned to provide detailed information on the soil and ground ice conditions in the immediate vicinity of the active pipeline test sections and also at the seven inactive test sections.

Terrain investigations, arctic test facility, Mountain River, N.W.T. / [R.M. Hardy and Associates](#) [Northwest Project Study Group](#) [Sponsor]

Edmonton, Alta. : R.M. Hardy and Assoc., 1971.

19 technical drawings ; 75 x 117 cm folded to 20 x 28 cm.

Drawings to accompany report of July 29/71 contained in envelope. This is an only copy. ASTIS record 31808.

Languages: English

Libraries: ACU TJ930 .R47 NO.984 V.1

These drawings present information on soil profiles and stratigraphy for the Mountain River test facility region. Information is derived from test holes and trench wall logs. Below 8 foot depth, interpolation between test holes was necessary. Test holes were drilled in November 1970. Datum for elevations is the arctic test facility datum. (ASTIS)

Report on terrain investigations, arctic test facility, Mountain River, N.W.T., volume 1, July 29, 1971 / [R.M. Hardy and Associates](#) [Northwest Project Study Group](#) [Sponsor]

Edmonton, Alta. : R.M. Hardy and Assoc., 1971.

1 v. (various pagings) : ill. (some col.), maps ; 30 cm.

ASTIS record 31809.

Languages: English

Libraries: ACU

This report covers work done in the field and in the laboratory by R.M. Hardy & Associates Limited for the Northwest Project Study Group at the Arctic Test Facility, Mountain River, N.W.T. during the period November 11, 1970 to January 31, 1971. A further report will be issued to cover the field work carried out during March of 1971. ... The object of the first investigation and report was simply to assess the suitability of the site for an Arctic Test Facility. The conditions desired at this test site included: a wide variety of soil and ground ice conditions, some organic terrain, a water course that could be blocked, thermokarst lakes or ponds, a source of dry borrow material, and reasonable access to scheduled air and water transportation. ...

Report on subsurface conditions active and inactive test sections, arctic test facility, Mountain River, N.W.T. / [R.M. Hardy and Associates](#) [Northwest Project Study Group](#) [Sponsor]

Edmonton, Alta. : R.M. Hardy and Assoc., 1971.

3 v. (various pagings) : ill. (some col.), maps ; 29 cm.

Volume 1 is accompanied by 14 folded drawings; volumes 2 and 3 consist of charts and tables.

ASTIS record 31810.

Languages: English

Libraries: ACU TJ930 .R47 NO.978 V.1

The attached report ... presents the results of soils and permafrost investigations and laboratory testing carried out in the field, and in our Edmonton laboratory, for the above project. Due to the large number of test hole logs and laboratory report sheets, this report has been bound in three volumes. Volume I contains the text of the report, maps, plans showing the test hole locations, charts, descriptive diagrams, photographs and a discussion of the variations which can be experienced in soil water content. Volume II contains the test hole logs and explanatory material on the symbols used on the test hole logs, the Radforth System for describing muskeg, the National Research Council system for describing ice in soils, and a brief review of the Atterberg System of classifying fine-grained soils. Volume III contains grain size analysis charts. ...

Terrain study, Mountain River, N.W.T. / [R.M. Hardy and Associates](#) [Northwest Project Study Group](#) [Sponsor]

Edmonton, Alta. : R.M. Hardy and Assoc., 1971.

2 v. (various pagings) : ill. (some col.), maps ; 29 cm.

ASTIS record 31811.

Languages: English

Libraries: ACU TJ930 .R47 NO.977 V.1

This report covers work done in the field and in the laboratory by R.M. Hardy & Associates Limited for Williams Brothers Canada Ltd., engineers for the Northwest Project Study Group in the vicinity of their Arctic Test Facility at Mountain River, N.W.T. The field work was performed during the period March 20 to April 2, 1971. ... The objectives of this drilling program ... included: obtaining more information on soil and ice types, studying certain terrain conditions e.g., thermokarst features, a statistical analysis of results from a large number of test holes, a study of the efficacy of certain in-situ testing methods, a study of the effects of various methods of clearing on depth of thaw, a study of the behaviour of certain foundation types during the spring and summer, an evaluation of the use of Gandhal frost tubes for measuring depth of thaw, a soils investigations for a trenching test program, provision of back-up services for other consultants as requested, and an investigation of the relative value of various sampling techniques and drilling methods which had not been used previously in this program. ...

Interim report - Arctic test facility, Mountain River, N.W.T. / [Williams Brothers Canada Limited](#) [Gas Arctic-Northwest Project Study Group](#) [Sponsor]

Calgary, Alta. : Williams Brothers Canada Ltd., 1972.

1 v. (various pagings) : ill. (some col.) ; 30 cm.

ASTIS record 31463.

Languages: English

Libraries: ACU TJ930 .P62 I567 1972

... The chief elements of the Arctic Test Facility are the Active Test Sections, buried sections of 48 inch diameter pipe through which air at subfreezing temperatures is circulated continuously. A part of the Active Test Sections is designed to provide the capability of circulating air at above freezing temperatures so that the effect of such temperatures can be observed. These events are termed "Cycling Tests". Many other

studies relating to construction and operation of a gas pipeline in the arctic environment are also performed at the Arctic Test Facility and are described in detail in this report. These studies include meteorological observations, construction studies, terrain investigation, vegetation studies, and corrosion/cathodic protection studies. ... Although this report deals mainly with three cycling tests undertaken to date, a limited amount of data have been included for the Cold Loop, as well as information on results obtained from other studies conducted at the test site.

**Developments and research on northern gas pipelines in Canada** / [Walker, G.W.](#)  
Calgary, Alta. : Canadian Arctic Gas Study Ltd., 1973.

10 leaves : 3 ill. ; 28 cm.

Presented at the International Gas Union, World Gas Conference, 12th, Nice, France, June 1973

ASTIS record 30447.

Languages: English

Libraries: ACU **TJ930 .P62 W34 1973**

Considering the unique conditions of the Arctic, the large distance and large volumes of gas to be moved, several alternate modes in addition to the vapour phase gas pipeline for transportation of the Arctic gas to the Canadian and U.S. markets have been evaluated. These included: (1) Liquefaction of the gas and moving it to the markets as LNG by pipeline, railway and airplanes. (2) Conversion to methanol and moving it by pipeline. (3) "Dense Phase" gas pipelining at operating temperatures from 200 degrees K. (-100 degrees F.) to 166 degrees K. (-160 degrees F.) and pressures from 6.894 MN/sq m (1000 psi) to 13.788 MN/sq m (2000 psi). These investigations concluded that the conventional buried vapour phase gas pipeline has an economic advantage over any of the above-mentioned alternatives. Consequently the research work has been oriented toward the problems associated with the design, construction and operation of a large diameter, high pressure gas pipeline. It has further been found that since the northern half of the proposed pipeline will cross areas of permafrost soils, some of which become unstable when thawed, the flowing gas temperature should be maintained below the freezing point of water. Thus the research work was further oriented towards the problems associated with a chilled gas pipeline in the permafrost areas and included studies in the following principal fields: (1) thermodynamics of gas flow (2) geotechnical and ground stability problems (3) surficial geology (4) ground temperature evaluation (5) protection of the environment (6) construction techniques (7) metallurgy. ... (Au)

**APPENDIX G**

**Nordegg Test Facility**

Test Facility	Nordegg Test Facility
Location	Nordegg, Alberta, Canada. Location of the existing Edson Mainline Pipeline
Owner	Alberta Gas Trunkline Limited (AGTL) Canadian Arctic Gas Study Limited (CAGSL) from 1972
Operator	AGTL & CAGSL
Participants	AGTL & CAGSL
Principal Researcher(s)	EBA Engineering
Timing / Duration	1971 – 1973
Purpose	To provide data for interpretation of ground temperature and heat flux readings adjacent to an operational pipeline
Description of tests	Monitoring of thermal regime associated with operation of the existing Edson Mainline Pipeline system.
Test Components	42” bermed loop section and the adjacent 30” mainline sections of pipeline.
Operating Conditions	Gas operated at above freezing temperature
Instrumentation	Thermal instrumentation in the soil surrounding the pipeline section
Summary of results	No results published.
Faults, problems, shortcomings	Not appropriate terrain or operating conditions to provide information on frost heave.
Requirements for further work	Thermal measurements used in early mathematical modeling of heat transfer. Data could be reviewed for further numerical model development. Considered a secondary data source.
Reports	As listed.
Availability / access to data	ASTIS & AINA call references listed (with abstract) where available

### Reference List:

Geotechnical engineering, Nordegg thermal research site / [E.W. Brooker & Associates Ltd.](#) [Gas Arctic Systems Study Group](#) [Sponsor]

[S.I.] : Elmer W. Brooker & Assoc. Ltd., 1971.

13, [40] leaves : ill. ; 28 cm.

ASTIS record 31826.

Languages: English

Libraries: ACU TJ930 .R47 NO.990

This report describes geotechnical conditions at the Nordegg Berm Thermal Research site operated by Gas Arctic Systems study group. A thirty inch main gas line near Nordegg,

Alberta and a 42 inch bermed experimental loop have been instrumented to study thermal aspects of soil and pipeline behavior. This data will ultimately be correlated with theoretical predictions from a mathematical model in the hope of verifying the usefulness of the model for application in an Arctic environment. ... The purpose of this investigation is to provide subsurface stratigraphic details to assist in interpretation of ground temperature and heat flux readings obtained from instrumentation previously installed by others. ... The nature of the backfill adjacent to the two pipes was also examined, and nuclear instruments installed in undisturbed soil to allow rapid determination of moisture content and density profiles. Sufficient laboratory testing was carried out to classify the various soil types identified at the site and allow an estimate of thermal soil properties based on existing correlations and data published by others.

## **APPENDIX H**

### **Norman Wells Chilled Gas Test Facility**

Test Facility	Norman Wells Chilled Gas Test Facility
Location	Norman Wells, NWT, Canada. Located on east flank of Mackenzie Valley, gentle slope uphill of a lake
Owner	Gas Arctic Systems (GAS) Canadian Arctic Gas Study Limited (CAGSL) from 1972
Operator	GAS & CAGSL
Participants	CAGSL EBA Engineering (engineering) EW Booker & Associates (engineering – geotechnical) Battelle Columbus Laboratories (engineering – thermal) Williams Brothers (construction)
Principal Researcher(s)	EBA Engineering, D. E. Fielder, NESL
Timing / Duration	1971 – 1973
Purpose	The Norman Wells Natural Gas Pipeline Research facility was constructed in order to provide a source of quantitative data characteristic of construction and operation of a large diameter pipeline in permafrost regions.
Description of tests	Operation of chilled and warm buried pipelines in ice rich permafrost. Quoted cost \$750k including construction, 1 yr operation & associated soils test program.
Test Components	4 operating pipe modules, 48” diameter, 120’ long, with bermed and ditched sections. Also 2, 42” diameter sealed static pipes to represent post-construction, pre-operation conditions.
Operating Conditions	4 operating section divided into: Hot berm (HB 65°F), hot ditch (HD 65°F), cold berm (CB 15°F) & cold ditch (CD 15°F) sections.
Instrumentation	Resistance temperature detectors, thermocouples, thermistors, plate foot settlement gauges, pneumatic piezometers, insitu nuclear moisture density probes and measurements of active layer thickness by probing to the permafrost table.
Summary of results	The test site settled an average 8” in areas of light activity away from pipe sections by the end of the first summer. Permafrost table regressed 6” from pre-construction active layer of 12-18”. Cold pipe modules showed some slumping of the berm before chilled operation. Thawing did not penetrate to below the pipe bottom so no settlement or heave recorded before start-up. After start-up, vertical movement at the edges of the berm showed heave up to 0.3’ then settlement 0.5’ during

	<p>the following summer. No movement of the backfilled half ditch despite thawing to 5' depth in summer 1972. One pipe module was held down by 10 frost anchors, but mobilized 1.5-2" giving a calculated heave pressure of 0.53tsf (7.4psi). Unfrozen soil extended just to bottom of pipe for short duration and was enough to initiate large uplift forces on refreeze. Hot pipe modules showed pipe settlement of 0.8' at the hot berm and 0.4' at the hot ditch. Static pipe modules showed lateral spreading and slumping of the berm material during the 1<sup>st</sup> &amp; 2<sup>nd</sup> thaw seasons. Depth of thaw was measured at 6' (2.5' below bottom of ditch) leading to 0.5' pipe settlement. Comparison of thaw depth profiles for different types and degrees of surface disturbance: fully disturbed, partially disturbed, burn areas, surface shields gave 36" in undisturbed areas to &gt;70" for fully disturbed. Thaw settlement prediction with Morgenstern &amp; Nixon 1-D model shows good correlation.</p>
Faults, problems, shortcomings	<p>The hot ditched pipe floated during spring run-off due to buoyancy of the plenum end. No anchoring was fitted due to late delivery of anchor saddles. The pipe was lowered back to the specified position by jetting below the plenum and with addition of metal ballast. Frost anchors then installed at ends of each pipe section to prevent uplift before operation. Berms slumped from 20-30" cover to 12-24" by end of summer 1971.</p>
Requirements for further work	<p>Good thermal data and some information on the effects of berm performance and thaw settlement. Data could be used to develop and calibrate geothermal models. Limited data on frost heave.</p>
Reports	As listed.
Availability / access to data	ASTIS & AINA call references listed (with abstract) where available

### Reference List:

Gas Arctic Project Norman Wells natural gas pipeline research facility :  
Instrumentation manual of operating instructions / [PEMCAN Services \(Pipeline Engineering and Management Services of Canada\)](#) [Gas Arctic Systems Study Group](#)  
[Sponsor]  
Calgary, Alta. : PEMCAN Services, 1971.  
[83] leaves (14 folded) : ill. (some folded) ; 29 cm.  
Cover title: Gas Arctic Systems Study Group Norman Wells natural gas pipeline research facility : instrumentation manual of operating instructions, November 10, 1971.  
ASTIS record 31868.

Languages: English

Libraries: ACU

This manual describes the operating procedures that are to be employed to take and record readings on the instruments placed in the soil at the Norman Wells Research Facility. The required frequency of reading of each of the instruments is set out. The following instruments are covered by this manual: (a) Troxler nuclear probes, (b) Terra Tec settlement sensors, (c) Terra Tec piezometers, (d) Plate foot settlement gauges, (e) Surface settlement gauges, (f) Pipe module settlement markers, (g) Battelle thermal conductivity probes, (h) Soil test moisture cells, (i) Copper-constantan thermocouples, (j) Thermistors, (k) Snow depth markers, (l) Thermal data acquisition system, 1. Resistance temperature detectors, 2. Heat flux transducers. Instructions on surveying profiles across pipe module berms are also included in this manual. Section "1" on the Thermal Data Acquisition System was written by Gas Arctic Systems.

Preliminary investigation of permafrost regression, Norman Wells test facility, Gas Arctic Project / [E.W. Brooker & Associates Ltd.](#) [Alberta Gas Trunk Line Company Limited](#) [Sponsor]

[S.I.] : Elmer W. Brooker & Assoc. Ltd., 1971.

7, 23 leaves : ill. (some folded) ; 30 cm.

ASTIS record 31818.

Languages: English

Libraries: ACU TJ930 .R47 NO.970

The Norman Wells test facility is set up to study possible thermal disturbances on permafrost due to pipeline construction. Instrumentation has been designed and fabricated in order to investigate factors related to permafrost thermal response as well as pipeline construction technique. A theoretical study regarding the thermal disturbance has been made. Methods of analysis have been programmed into computer codes. Soil investigations of the test site have been carried out and their results used to provide input data for the analysis. Verification of the theoretical work depends upon its prediction of the performance of the pipe line test loops. Measuring devices are to be installed to monitor performance. In order to investigate the validity of the instrumentation, it is imperative to study the predicted thermal response of the permafrost prior to the operation of the test facility. Four test modules have been set up, incorporating two types of construction (trench backfill and berm backfill) and two operating gas temperatures (15 degrees F and 65 degrees F). In this report, investigations of temperature regression have been made only for the hot-berm module. ... These investigations serve as design bases for instrumentation including, temperature sensors, thermal conductivity probes, settlement gauges, piezometers, density and moisture content gauges.

Norman Wells natural gas pipeline research facility : instrumentation : installation and initial performance / [PEMCAN Services \(Pipeline Engineering and Management Services of Canada\)](#) [Gas Arctic Systems Study Group](#) [Sponsor]

Calgary, Alta. : PEMCAN Services, 1972.

ca. 200 leaves : ill. (some col.) ; 29 cm.

ASTIS record 31869.

Languages: English

Libraries: ACU TJ930 .R47 NO.1129

This report describes the installation of instruments at the Norman Wells Research Facility. These instruments have been designed to measure the response of the permafrost subsurface to the construction and operation of a gas pipeline in six simulated configurations. A brief description of each instrument, of the soil properties to be measured and of the performance of the instruments to the end of December 1971, has been included. While the number of inoperative instruments is higher than anticipated, most of the remainder appear at this early stage to be functioning satisfactorily and show promise of providing the data required.

Norman Wells Natural Gas Pipeline Research Facility : evaluation of geotechnical data / [EBA Engineering Consultants Ltd.](#), [Canadian Arctic Gas Study Limited](#) [Sponsor]  
Calgary, Alta. : EBA Engineering Consultants Ltd., 1974.  
52, 30, 15, 29, [19] leaves : ill. (some folded) ; 29 cm.

ASTIS record 31819.

Languages: English

Libraries: ACU

The Norman Wells Natural Gas Pipeline Research facility was constructed in order to provide a source of quantitative data characteristic of construction and operation of a large diameter pipeline in permafrost regions. Instrumentation was installed to monitor behavior of the pipe and supporting soil. This report presents geotechnical data collected from vertical movement indicators, pore pressure transducers and nuclear moisture density access tubes. The data is evaluated with regard to tentative pipeline design application and the applicability of several theories pertaining to thawing soils are examined. ...Experimental surface coverings were found to retard the thaw significantly during the summer, however by fall thaw was continuing at the same rate under the shields whereas it had reduced significantly in other areas. The surface covering experiment was affected to a serious extent by two dimensional edge effects since the width of shield was not large relative to the depth of thaw. ...

Norman Wells natural gas pipeline research facility : site selection, instrumentation selection, test site construction / [Gas Arctic Systems Study Group](#)  
[S.l.] : Gas Arctic Systems Study Group, 1972.  
[50] leaves : ill. (some col.) ; 29 cm.

ASTIS record 31866.

Languages: English

Libraries: ACU

This report details the site selection, the construction of the test facility and the selection of associated instrumentation to monitor the thermal and geotechnical disturbances. Test site results will aid in the development and verification of a flexible computer analysis program for predicting the important elements of the pipe-soil interaction, and thereby allow the prediction of proper solutions to problems to be encountered along the entire proposed pipeline.

Norman Wells Natural Gas Pipeline Research Facility : subsurface conditions / [PEMCAN Services \(Pipeline Engineering and Management Services of Canada\)](#) [Gas Arctic Systems Study Group](#) [Sponsor]

[S.I.] : PEMCAN Services, 1972.

ca. 300 leaves : ill. ; 29 cm.

ASTIS record 31821.

Languages: English

Libraries: ACU TJ930 .R47 NO.967

This report describes the findings of an investigation of the subsurface conditions at the Norman Wells Research Facility, carried out at various times from April 13 to September 17, 1971. The soil and ice conditions encountered are presented in the form of field descriptions and classifications, laboratory test results, subsurface sections and photographs.

Thermal test facilities supplementary proposal for the Alberta Gas Trunk Line Company Limited / [PEMCAN Services \(Pipeline Engineering and Management Services of Canada\)](#) [Alberta Gas Trunk Line Company Limited](#) [Sponsor]

Calgary, Alta. : PEMCAN Services, 1971.

[43] leaves : ill. ; 29 cm.

ASTIS record 31867.

Languages: English

Libraries: ACU TJ930 .R47 NO.1131

This report presents PEMCAN's supplementary proposal to develop a test facility in the region of Norman Wells for the purpose of providing information for studies to be undertaken in the design and development of a natural gas pipeline from Prudhoe Bay, Alaska to Alberta. In undertaking thermal calculations, the factors that have an influence on the heat flow to and from the pipe include: climatic conditions, type of ground cover, topography, orientation of pipe line, type and condition of soil, mode on construction, and disturbance of adjacent terrain due to construction activities.

Norman Wells natural gas pipeline research facility : thermal data reduction and presentation procedures / [Canadian Arctic Gas Study Limited](#)

[S.I.] : Canadian Arctic Gas Study Ltd., 1973.

ca. 200 leaves : ill. ; 29 cm.

ASTIS record 31864.

Languages: English

Libraries: ACU TJ930 .R47 NO.1099

When Gas Arctic Systems made the decision to construct a Natural Gas Pipeline Research Facility at Norman Wells, N.W.T., it was recognized that as one of the major objectives was the collection of large quantities of thermal data, the reduction and presentation of those data in a form suitable for use by research scientists could be an onerous task. ... This report has been prepared to record the input parameters, equations, and analytic methods used in the reduction and presentation of thermal data. ...

Preliminary investigation of permafrost regression : Norman Wells test facility / [E.W. Brooker & Associates Ltd.](#) [Arctic Systems Study Group](#) [Sponsor] [Alberta Gas Trunk Line Company Limited](#) [Sponsor]

[Edmonton, Alta.] : E.W. Brooker Assoc. Ltd., 1971.

[33] leaves (15 folded) : ill. (some folded) ; 29 cm.

(Geotechnical report, no. 3)

Contains four folded drawings in map pocket.

ASTIS record 31697.

Languages: English

Libraries: ACU TJ930 .R47 NO.970

The Norman Wells test facility is set up to study possible thermal disturbances on permafrost due to pipeline construction. Instrumentation has been designed and fabricated in order to investigate factors related to permafrost thermal response as well as pipeline construction technique. A theoretical study regarding the thermal disturbance has been made. Methods of analysis have been programmed into computer codes. Soil investigations of the test site have been carried out and their results used to provide input data for the analysis. ... Four test modules have been set up, incorporating two types of construction (trench backfill and berm backfill) and two operating gas temperatures (15 degrees F and 65 degrees F). In this report, investigations of temperature regression have been made only for the hot-berm module. The other three are to be investigated and will be reported at a later date. These investigations serve as design bases for instrumentation including, temperature sensors, thermal conductivity probes, settlement gauges, piezometers, density and moisture content gauges.

Preliminary analyses of geotechnical data from Norman Wells test site : report no. 15 / [E.W. Brooker & Associates Ltd.](#) [Gas Arctic Systems Study Group](#) [Sponsor]

[Edmonton, Alta.] : E.W. Brooker Assoc. Ltd., 1972.

[24] leaves (2 folded) ; ill. (2 folded) ; 29 cm.

(Geotechnical report, no. 15)

ASTIS record 31708.

Languages: English

Libraries: ACU TJ930 .R47 NO.964

A preliminary analysis of the geotechnical data obtained from the Norman Wells Test Site has been undertaken. The purpose of this analysis is to assess the validity of applying the thaw consolidation theory (Morgenstern and Nixon 1971) to the case of a heated pipeline. ... The assumptions made in the formulation of the thaw consolidation theory are provided in the original publication, however, a review of the major assumptions used will be given here in order to establish the basis for this analysis. ... The theory applies to one-dimensional thaw consolidation. That is, heat flow and seepage occur in a vertical direction only. Furthermore, the heat source is assumed to be a step change in temperature of infinite extent applied at the surface. Clearly, the case of a heated pipeline does not meet these requirements. It is apparent, however, that these requirements are met reasonably well in the area immediately below the centre line of the pipeline. The analysis concentrates therefore on the conditions which develop directly below the pipeline. This simplified approach is felt to be valid since the behavior of the pipeline is dominantly affected by the conditions directly beneath it.

Gas Arctic Systems permafrost regression analysis : report no. 16 : Progress report for review meeting no. 8 / [E.W. Brooker & Associates Ltd.](#) [Gas Arctic Systems Study Group](#) [Sponsor]

[Edmonton, Alta.] : E.W. Brooker Assoc. Ltd., 1972.

[71] leaves : ill. ; 29 cm.

(Geotechnical report, no. 16)

ASTIS record 31709.

Languages: English

Libraries: ACU TJ930 .R47 NO.964

General progress of the geotechnical section of the Soil Behavior Study Group (April 18 to June 5, 1972) is discussed in this report. The report is organized as a series of independent brief report contributions by the various individuals involved at Brooker Associates, presented in Appendices A to G. These Appendices refer specifically to areas for further study as presented in the report on Review Meeting No. 7 by Dr. R.N. Yong. The text of this report summarizes the findings at these various areas of investigation and conclusions are drawn from them which will help direct future endeavors. ... Preliminary analysis of the geotechnical data obtained from the Norman Wells Test Site has been completed. The results are very encouraging (Appendix A) and indicate that for at least the first year of operation the idealized theory of thaw consolidation will provide realistic predictions. ...

**Developments and research on northern gas pipelines in Canada** / [Walker, G.W.](#)

Calgary, Alta. : Canadian Arctic Gas Study Ltd., 1973.

10 leaves : 3 ill. ; 28 cm.

Presented at the International Gas Union, World Gas Conference, 12th, Nice, France, June 1973

ASTIS record 30447.

Languages: English

Libraries: ACU **TJ930 .P62 W34 1973**

Considering the unique conditions of the Arctic, the large distance and large volumes of gas to be moved, several alternate modes in addition to the vapour phase gas pipeline for transportation of the Arctic gas to the Canadian and U.S. markets have been evaluated. These included: (1) Liquefaction of the gas and moving it to the markets as LNG by pipeline, railway and airplanes. (2) Conversion to methanol and moving it by pipeline. (3) "Dense Phase" gas pipelining at operating temperatures from 200 degrees K. (-100 degrees F.) to 166 degrees K. (-160 degrees F.) and pressures from 6.894 MN/sq m (1000 psi) to 13.788 MN/sq m (2000 psi). These investigations concluded that the conventional buried vapour phase gas pipeline has an economic advantage over any of the above-mentioned alternatives. Consequently the research work has been oriented toward the problems associated with the design, construction and operation of a large diameter, high pressure gas pipeline. It has further been found that since the northern half of the proposed pipeline will cross areas of permafrost soils, some of which become unstable when thawed, the flowing gas temperature should be maintained below the freezing point of water. Thus the research work was further oriented towards the problems associated with a chilled gas pipeline in the permafrost areas and included studies in the following

principal fields: (1) thermodynamics of gas flow (2) geotechnical and ground stability problems (3) surficial geology (4) ground temperature evaluation (5) protection of the environment (6) construction techniques (7) metallurgy. ... (Au)

**APPENDIX I**

**Prudhoe Bay Test Facility**

<b>Test Facility</b>	<b>Prudhoe Bay Test Facility</b>
Location	Deadhorse, Alaska, USA
Owner	Gas Arctic Systems
Operator	Gas Arctic Systems
Participants	Gas Arctic Systems Study Group Members: Alberta Gas Trunk Line Company Ltd, Columbia Gas System, Northern Natural Gas Company, Texas Eastern Transmission Corporation, Canadian National Railway. Pipe Line Technologists Inc. (Consultant) Battelle Engineering (Engineering & Construction) EW Brooker & Associates (Engineering)
Principal Researcher(s)	Battelle Engineering
Timing / Duration	1971 – 1972 (major phase)
Purpose	Objective was to develop, by means of the design, construction and operation of an instrumented research facility, the information necessary for an engineering design to construct and operate a reliable gas pipeline through the far north with a minimum effect on the environment
Description of tests	Pipeline installed fully trenched and half-bermed in ice rich permafrost. Quoted cost \$2million for construction, 1 yr operation & associated soil test program.
Test Components	1, 48” pipeline loop incorporating half bermed burial with 18” and 30” cover on one leg, and fully trenched with 30” cover in the other leg. Trenched leg excavated by blasting and backfilled with natural soil, and by stitch drilling and excavation backfilled with gravel. 2 static (dormant) sections also installed, 120’ long, 4’ diameter capped at the ends, installed in buried and bermed conditions.
Operating Conditions	Pipeline operated nominally at 25°F.
Instrumentation	Instrumentation included comprehensive arrays of thermocouples at 5 planes perpendicular to the pipe as well as away from the pipe to monitor undisturbed soil and the effect of construction. Heat flux transducers on the pipe surface, strain gauges in 2 directions to measure bending in both directions, and level poles attached to pipe & sleeved through soil. Static sections instrumented with thermocouples
Summary of results	Initial results showed bermed sections gave little temperature change over the first summer at 4’ depth

	<p>(construction disturbance was only 3') and temperatures dropped from October. Effects of thermal inertia near thaw pond giving higher moisture contents may explain differences observed between the different sections. Temperature for the trenched pipe was significantly higher at 12' depth in December than bermed sections, possibly due to the 8' construction disturbance. The zone of influence of soil temperature to the chilled pipe operation was limited to 6" to 12" in first 6 months. Near ground temperatures were warmer in the gravel section due to higher thermal conductivity of gravel. Ground temperature near the buried (trenched) pipe was never &gt;32°F, and no pipe movement measured. Temperature around the bermed section was &gt;32°F but the pipes were close to neutral buoyancy so no horizontal pipe movement measured. Vertical displacement from leveling &amp; bending moments from strain gauges showed that most movement occurred during the simulated hydro test. The buried leg raised 1.5-2" at the NW corner during the hydrotest at 40°F but no appreciable movement measured since. This is attributable to longitudinal thermal expansion of line being more pronounced on the buried portion and due to buoyancy effects. Further uplift was stopped by anchor strapping. Moments in the pipe were small compared to allowable values (2-3%). Average active layer depth across the site was 10". The bermed pipe sections depressed the permafrost table by 2-4". Bermed section showed the formation of a large cavity above the pipe, thought to be due to melting of ice and arching of the soil.</p>
<p>Faults, problems, shortcomings</p>	<p>Initial problems included drifting of temperature recording system due to changes in ambient temp in instrument room. Measurements were corrected by comparing to ice bath readings. Ice build-up of 0.5" on inside wall of pipes causing concern on heat transfer coefficients in the loop. Defrost cycles were incorporated into the operation procedure 1-3 times a week, removing 15-20 gallons of water each time. The problem was eliminated by October. Hydrostatic test simulation July 14-21 at 40°F. Cold air flow started in July, but slow cool-down due to problems with refrigeration compressor – temp decreased to 27°F in 10 days. Generator failure forced occasional shutdown. Dormant section floated out of the ground and extensive thaw settlement occurred over the chilled section during chilling shut-down.</p>

Requirements for further work	Some data on geothermal processes, heat flux and geotechnical properties. Value of data limited due to erratic operation due to power failures. Limited value for frost heave and thaw settlement analysis.
Reports	As listed.
Availability / access to data	ASTIS & AINA call references listed (with abstract) where available

### Reference List:

**Report on laboratory tests for thermal and engineering soil properties, Gas Arctic Systems Prudhoe Bay pipeline test site, Deadhorse, Alaska / [R&M Engineering & Geological Consultants](#) [Battelle Memorial Institute](#). [Columbus Laboratories](#) [Sponsor]**

Fairbanks, Alaska : R&M Engineering & Geological Consultants, 1972.

37, 4, 11, 20, 9, 2, 42 leaves : ill. (some folded), 1 map ; 28 cm.

ASTIS record 31831.

Languages: English

Libraries: ACU

... The purpose of this report is to present: 1. An interpretation and description of general geologic and subsurface soil and ice conditions existing at the Prudhoe Bay test site. 2. The results of laboratory thermal conductivity tests performed on samples removed from the vicinity of the instrument planes. 3. Laboratory test results for all soil samples received from the test site. Part I of this report presents all general information and test results. Part II contains photographic logs of all core samples submitted from the second drilling program.

**Report on subsurface soil investigations, Gas Arctic Systems Prudhoe Bay pipeline test site, Deadhorse, Alaska, part III / [R&M Engineering & Geological Consultants](#) [Battelle Memorial Institute](#). [Columbus Laboratories](#) [Sponsor]**

Fairbanks, Alaska : R&M Engineering & Geological Consultants, 1972.

5, [6] leaves : ill. (1 folded) ; 28 cm.

ASTIS record 31832.

Languages: English

Libraries: ACU **TJ930 .R47NO.1119**

As a part of Gas Arctic Systems tests of the performance of a large diameter gas pipeline under various soil and climatic conditions, a test facility was constructed at Deadhorse near Prudhoe Bay on the Alaskan Arctic Coastal Plain. This facility has been described in detail in Part I of this series of reports and the reader is referred to this earlier submittal if more details are required. Previously, two separate subsurface investigations had been performed at the test site. The first program consisted of five, six inch diameter test holes drilled at the southwest corner of the test loop. The second program consisted of five, 36 inch diameter test holes, one at each of the instrument planes and one near the reference plane. It was determined that more information was needed in order to enable accurate subsurface profiles to be constructed at the instrument planes. The purpose of this study was to provide the information necessary to construct the needed profiles.

**Developments and research on northern gas pipelines in Canada** / [Walker, G.W.](#)

Calgary, Alta. : Canadian Arctic Gas Study Ltd., 1973.

10 leaves : 3 ill. ; 28 cm.

Presented at the International Gas Union, World Gas Conference, 12th, Nice, France, June 1973

ASTIS record 30447.

Languages: English

Libraries: ACU **TJ930 .P62 W34 1973**

Considering the unique conditions of the Arctic, the large distance and large volumes of gas to be moved, several alternate modes in addition to the vapour phase gas pipeline for transportation of the Arctic gas to the Canadian and U.S. markets have been evaluated. These included: (1) Liquefaction of the gas and moving it to the markets as LNG by pipeline, railway and airplanes. (2) Conversion to methanol and moving it by pipeline. (3) "Dense Phase" gas pipelining at operating temperatures from 200 degrees K. (-100 degrees F.) to 166 degrees K. (-160 degrees F.) and pressures from 6.894 MN/sq m (1000 psi) to 13.788 MN/sq m (2000 psi). These investigations concluded that the conventional buried vapour phase gas pipeline has an economic advantage over any of the above-mentioned alternatives. Consequently the research work has been oriented toward the problems associated with the design, construction and operation of a large diameter, high pressure gas pipeline. It has further been found that since the northern half of the proposed pipeline will cross areas of permafrost soils, some of which become unstable when thawed, the flowing gas temperature should be maintained below the freezing point of water. Thus the research work was further oriented towards the problems associated with a chilled gas pipeline in the permafrost areas and included studies in the following principal fields: (1) thermodynamics of gas flow (2) geotechnical and ground stability problems (3) surficial geology (4) ground temperature evaluation (5) protection of the environment (6) construction techniques (7) metallurgy. ... (Au)

Engineering Design and Construction of a Gas Pipeline Research Facility at Prudhoe Bay, Alaska. Battelle Engineering May 1972 TJ930.P62.R4647. 1972 C1

Completion Report, Prudhoe Bay Test Facility, Pipe Line Technologists Inc. August 1971. TJ 930. R47. No 1317 & 1318.

Engineering and Environmental Factors related to the Design, Construction and Operation of a Natural Gas Pipeline in the Arctic Region (Based on the Prudhoe Bay, Alaska, Research Facility), Battelle Columbus Laboratories. Final Report. March 1974. Vols I – IV + Supplementary Report on Latent Berm Effects.

**APPENDIX J**

**Quill Creek Test Facility**

Test Facility	Quill Creek Test Facility
Location	Yukon Territory, 165km SE of Alaska border
Owner	Foothills Pipe Lines (Yukon)
Operator	Foothills Pipe Lines (Yukon)
Participants	Alberta Gas Trunkline Limited (AGTL) West Coast Transmission
Principal Researcher(s)	J. R. Ellwood, D. E. Fielder, L. E. Carlson
Timing / Duration	1981 -
Purpose	The purposes of test site were (1) to study construction methods for the installation of large diameter pipelines in permafrost, (2) to observe the effectiveness of mitigative designs in minimizing thaw settlement, (3) to study the behaviour of cuts in ice rich hills, and (4) to provide data on the thermal behaviour of design modes for comparison with thermal model predictions.
Description of tests	Activities included (1) sidehill grading with various methods of protecting & stabilizing cuts in ice rich hills, (2) disposal area for storage of ice rich soils from sidehill cuts, (3) buoyancy control using granular fill as pipeline buoyancy control, (4) permafrost mitigative design construction for warm pipeline operation.
Test Components	Pipe sections placed on a 1m thick gravel pad, with 100mm polystyrene insulation embedded 300mm from the base. Pipeline laid on the gravel pad and covered with gravel or concrete segments to protect against low ambient temperature, damage & restrain against movements due to temperature & pressure. 3 pipe sections covered by gravel with zero, 100mm & 200mm urethane insulation coating. 2 sections covered in concrete segments including urethane insulation in saddle.
Operating Conditions	All pipes maintained at +15°C by air heating system.
Instrumentation	Matrix of thermistors placed within & below gravel pads to record frost line.
Summary of results	Uninsulated pipe in gravel showed growth of the thaw bulb under the pipe, with the warm pipe preventing seasonal freezing of the gravel and soil below. Analysis suggests continued growth of thaw bulb would occur longterm. Insulated pipes show complete thawing of the gravel during summer and complete refreeze during winter. Concrete sections constructed in summer using

	warm gravel pads over the 0.5m thick thawed active layer increased thaw to 2m due to construction. 1 year of operation shows the thaw depth approximately constant with active layer not quite refrozen. Thermal analysis agrees well with measurements of 0°C isotherm. Measured settlements approximately 160mm after 22 months in the gravel sections (insulated & noninsulated) and 50mm in concrete sections after 16 months (later start date). Attributed to consolidation of small amounts of seasonal thawing due embankment placement. This correlates with an unheated pipe section which showed similar settlement. Concrete section showed less settlement due to installation in summer and consolidation occurring before startup and monitoring. Sidehill cut tests showed that use of mesh & jute covering could stabilize cut slopes in ice rich soils.
Faults, problems, shortcomings	
Requirements for further work	Data could be used for thaw settlement data and geothermal modeling
Reports	As listed. Very little data in the public domain
Availability / access to data	ASTIS & AINA call references listed (with abstract) where available

### Reference List:

Testing pipelining techniques in warm permafrost / [Carlson, L.E.](#) [Butterwick, D.E.](#)  
 In: Permafrost : Fourth International Conference, proceedings, July 17-22, 1983. -  
 Washington, D.C. : National Academy Press, 1983, p. 97-102, figures, table  
 ASTIS record 14550.

Languages: English

Libraries: ACU 6B441.I562 4<sup>th</sup> 1983

A thaw settlement research facility was built by Foothills Pipe Lines (Yukon) Ltd. as part of the permafrost engineering design for the Alaska Highway Gas Pipeline Project. The main purposes of the test facility were (1) to study construction methods for the installation of large diameter pipelines in permafrost, (2) to observe the effectiveness of mitigative designs in minimizing thaw settlement of the pipe and right-of-way surface, (3) to study the behavior of cuts in ice rich hills, and (4) to provide data on the thermal behavior of design modes for comparison with thermal model predictions. This paper discusses the observations of the pipeline design performance and the comparison of that performance with initial predictions.

### **Frost Heave and Thaw Settlement Test Facilities** / Carlson, L. E.

Pipelines and Frost heave. 1985. Proceedings of a Conference, Caen, France. Sponsored by Energy, Mines and Resources, Canada and Ministère de l'Urbanisme et du Logement, France. 75 pp. Carleton University, Ottawa, Canada.

## **Appendix K**

### **Selected Figures & Photographs Relating to Full-Scale Test Facilities**

## **Caen Frost Heave Test Facility**



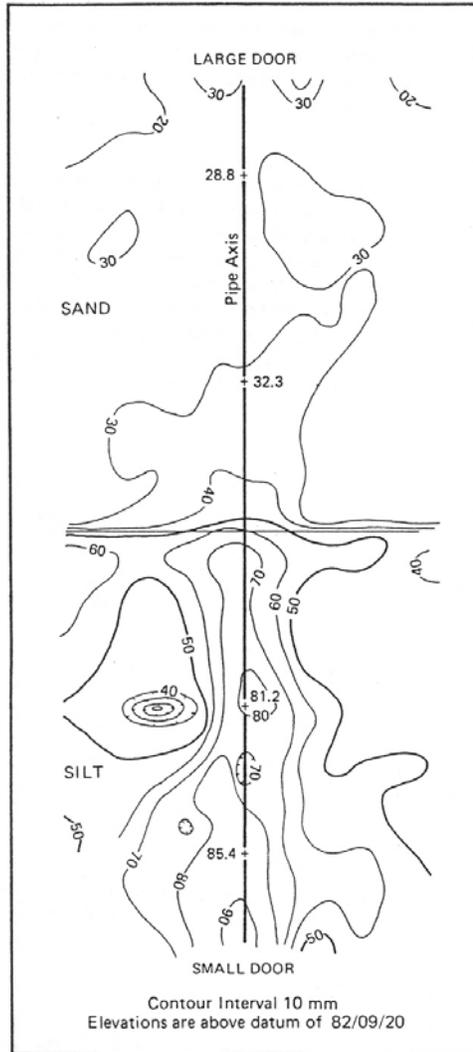


Figure 3.6 Elevation of soil surface. 83/01/05

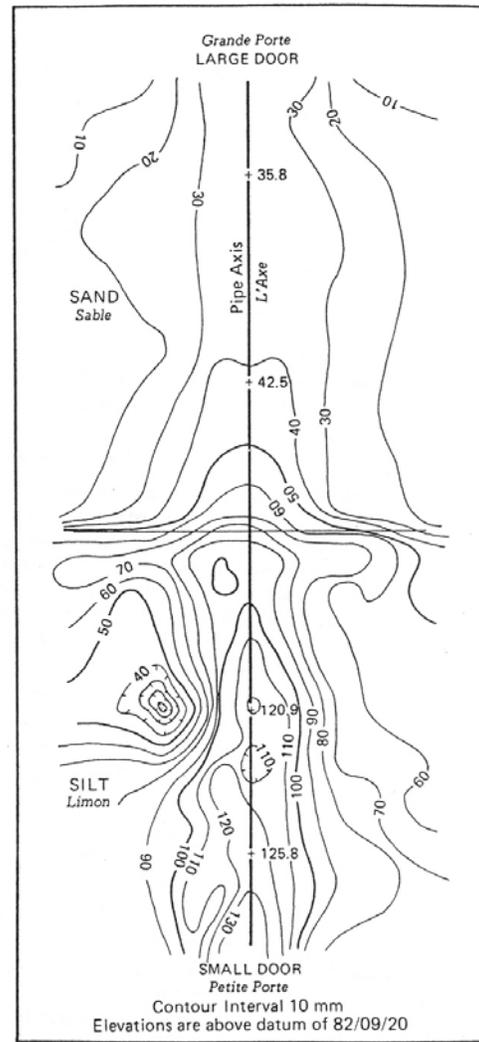


Figure 3.7 Elevation of soil surface. 83/06/07  
End of first freeze period

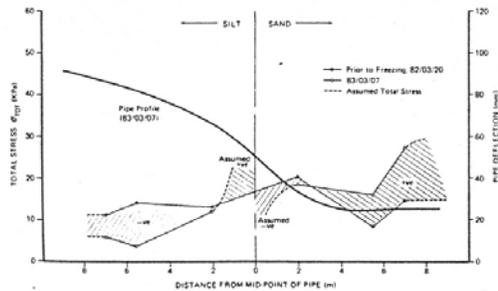


Figure 3.8 Total stress in soil beneath pipe during first freeze period (83/03/07)  
(Pressure cells located initially 46 cm beneath pipe)

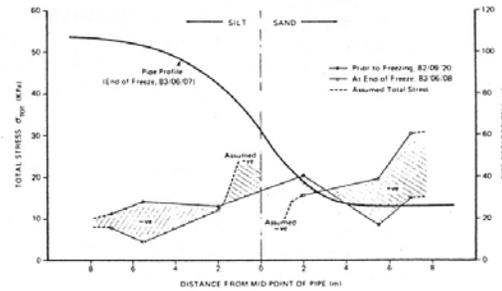
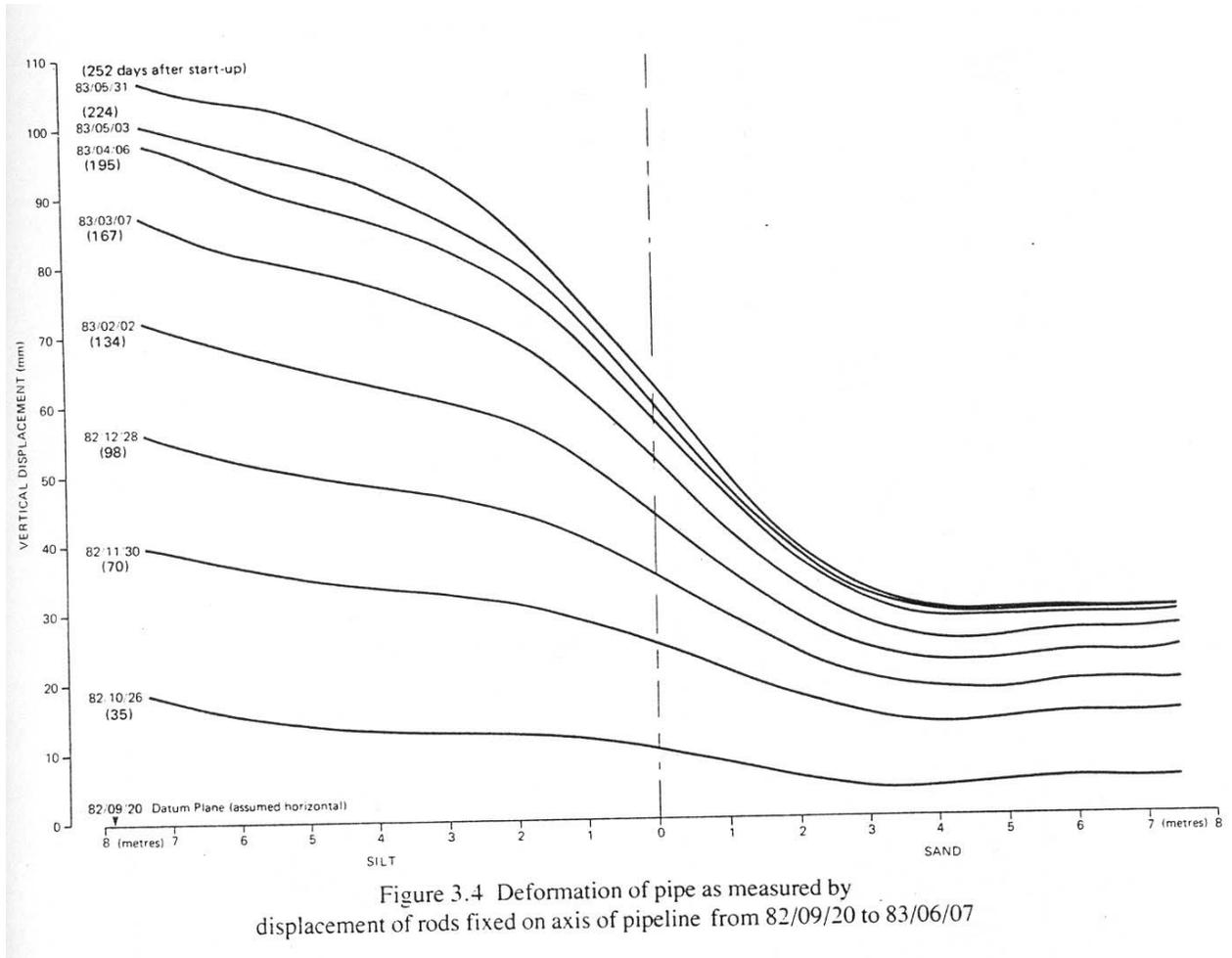


Figure 3.9 Total stress in soil beneath pipe at end of first freeze period (83/06/08)  
(Pressure cells are located initially 46 cm beneath pipe)

Sample Measurements of Soil and Pipe Behaviour (After Pipelines and Frost Heave 1985)



Measured Pipe Heave (After Pipelines and Frost Heave 1985)

## **Calgary Frost Heave Test Facility**

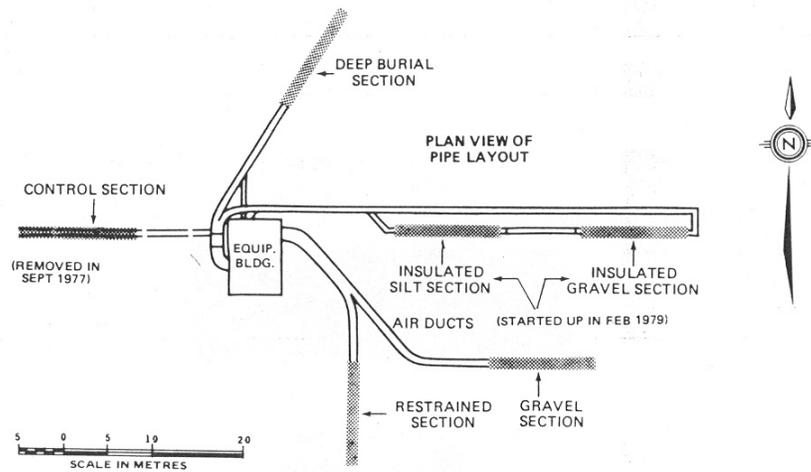
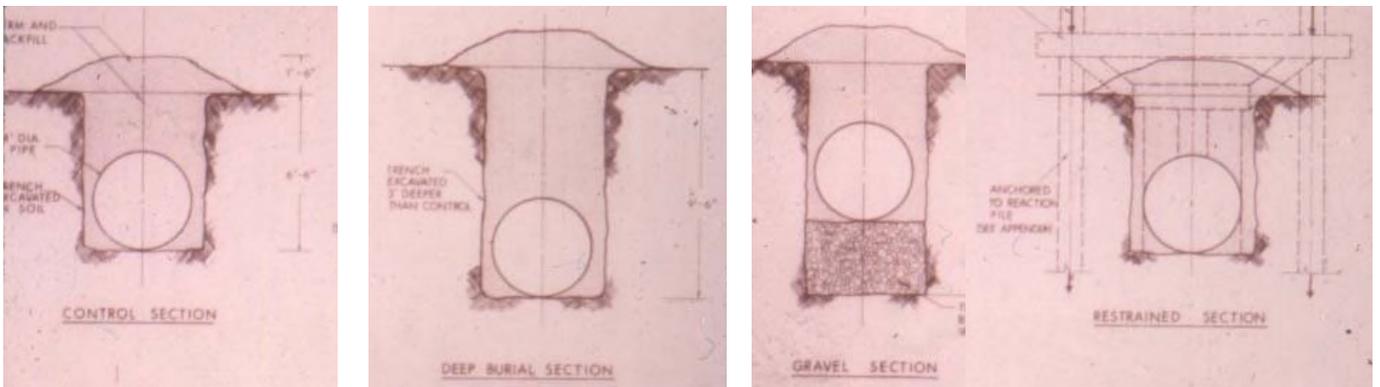
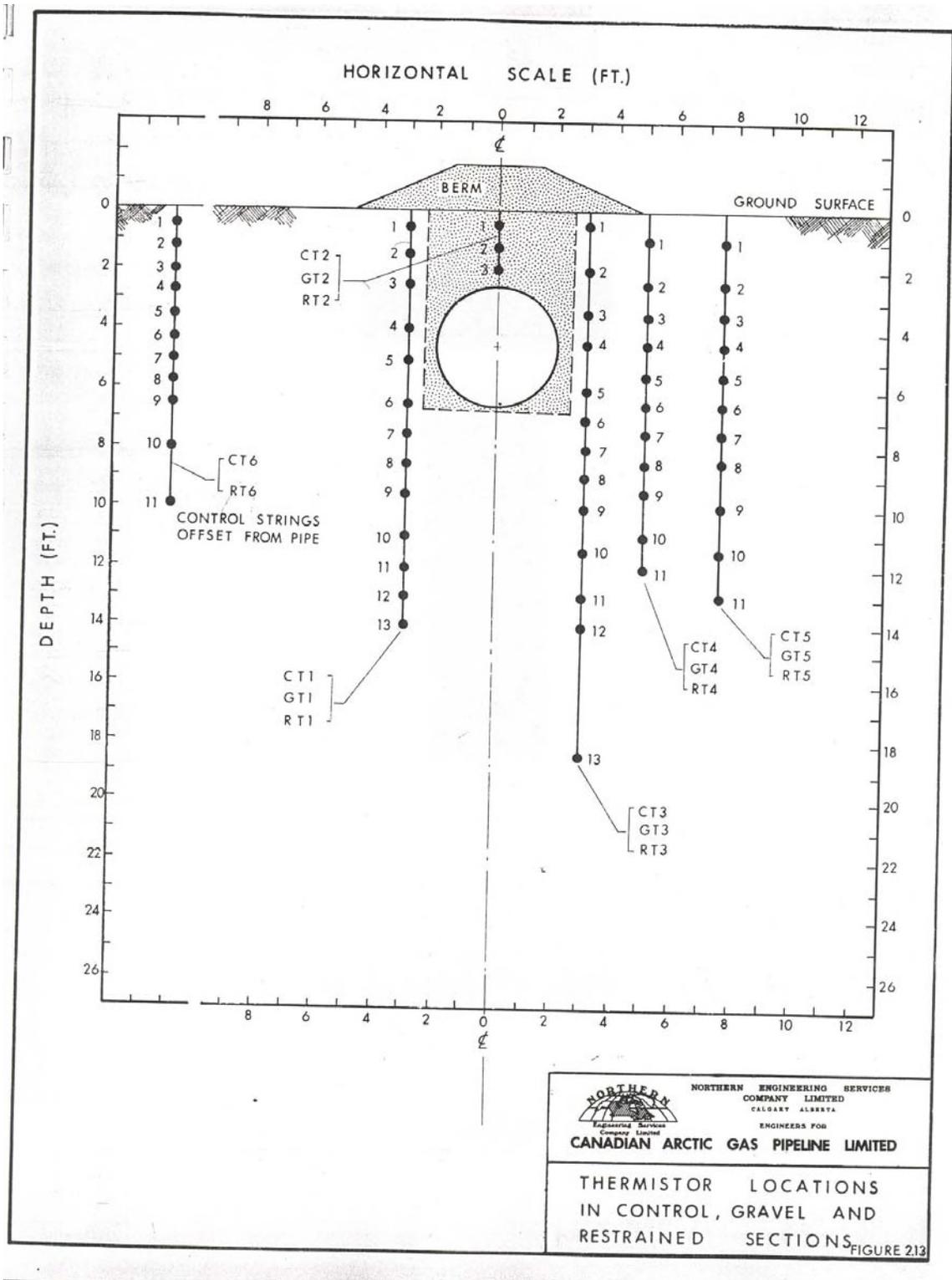


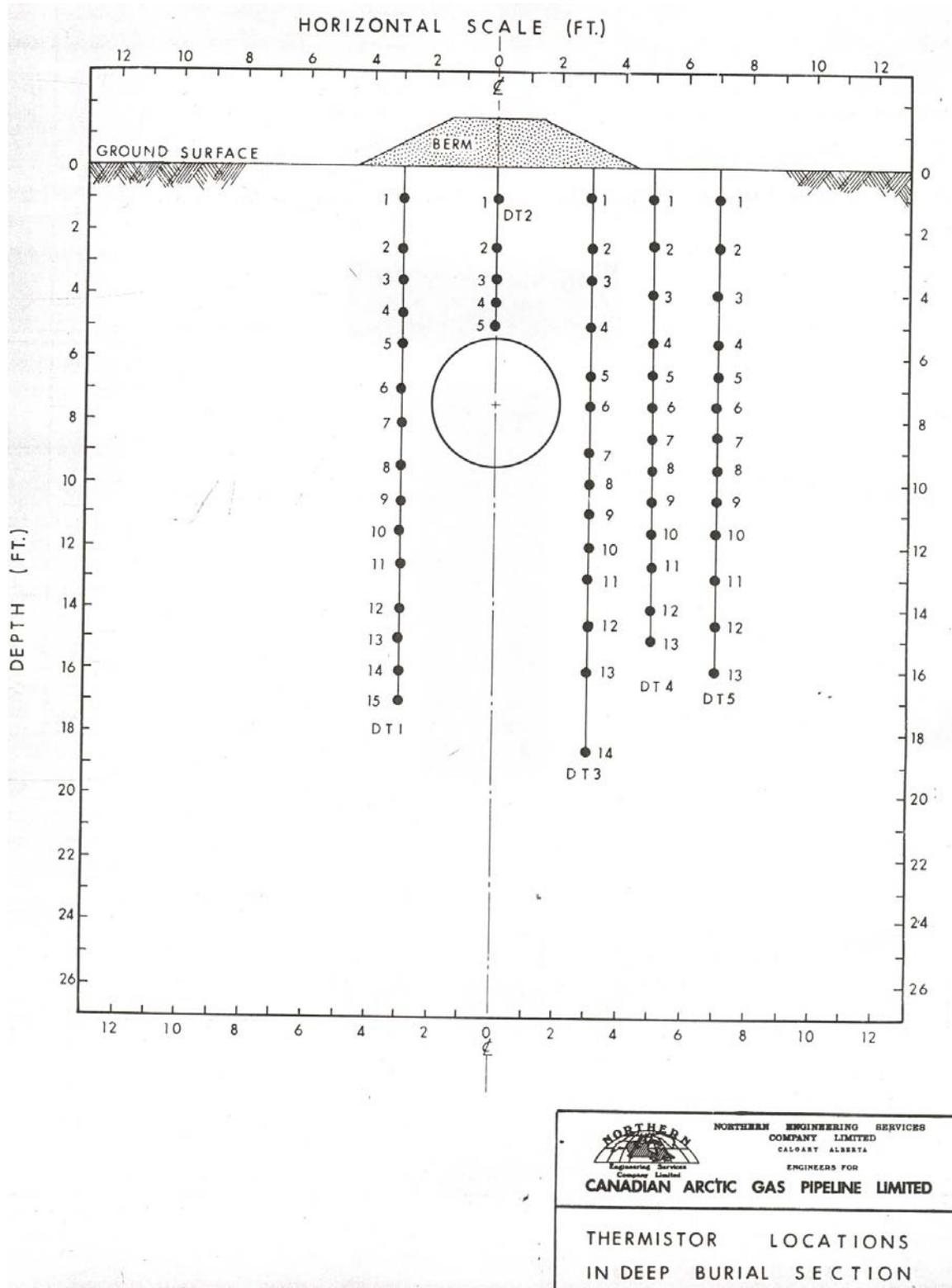
FIGURE 1. Schematic layout of Calgary frost heave test facility.

### Test Site Layout (After Carlson et al 1981)



### Burial Configurations of Initial Pipe Sections (From JICA Library)





Instrumentation Location – Deep Burial Section (After NES 1976)

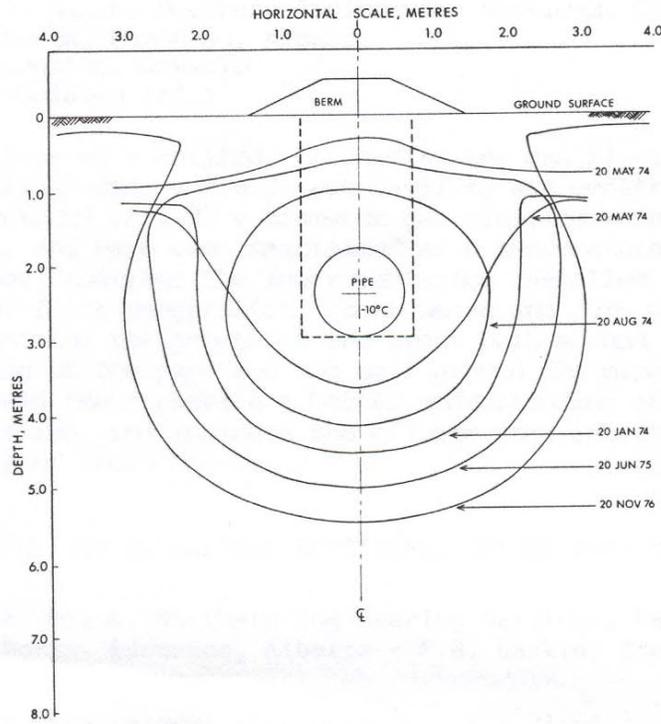


FIGURE 3 FROST PENETRATION AROUND DEEP BURIAL SECTION

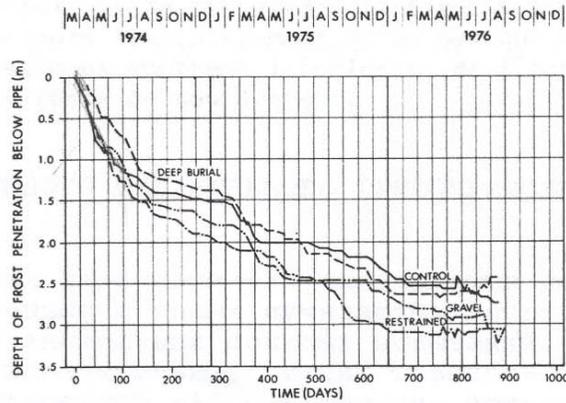


FIGURE 4 FROST PENETRATION BELOW PIPE SECTION

Typical Measurements During Test (After Slusarchuk et al 1978)

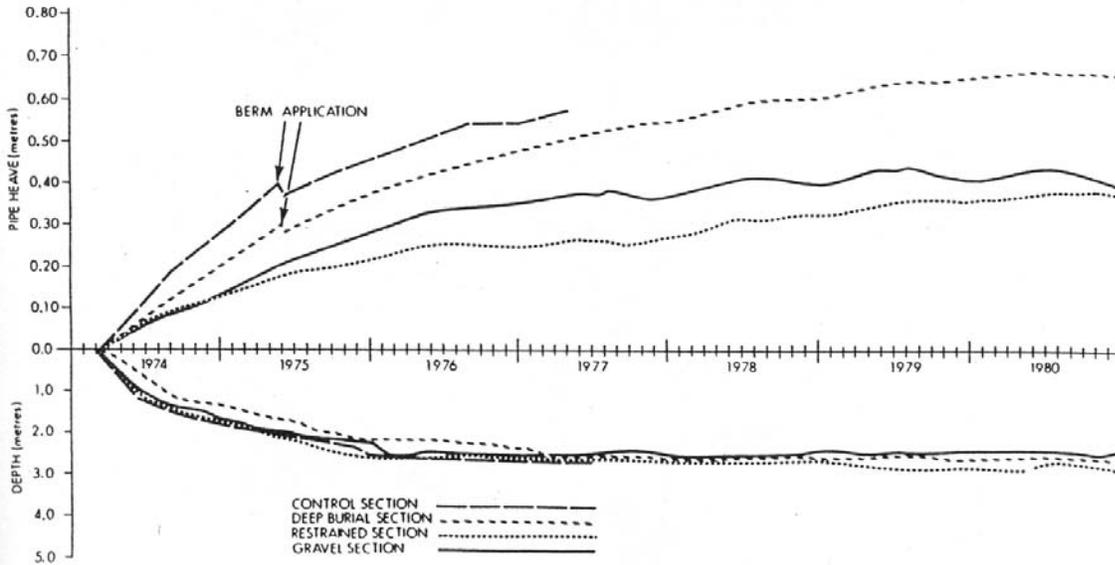


Figure 2 Calgary frost heave test facility — observed pipe heave and depth of frost below bottom of pipe

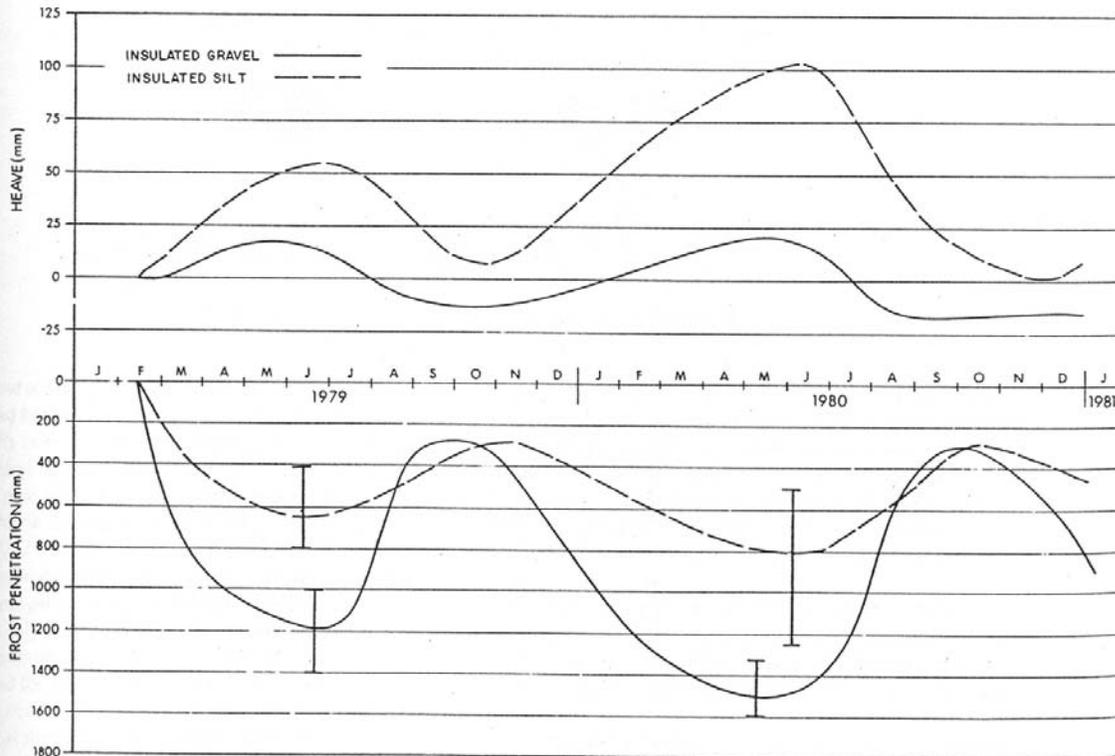
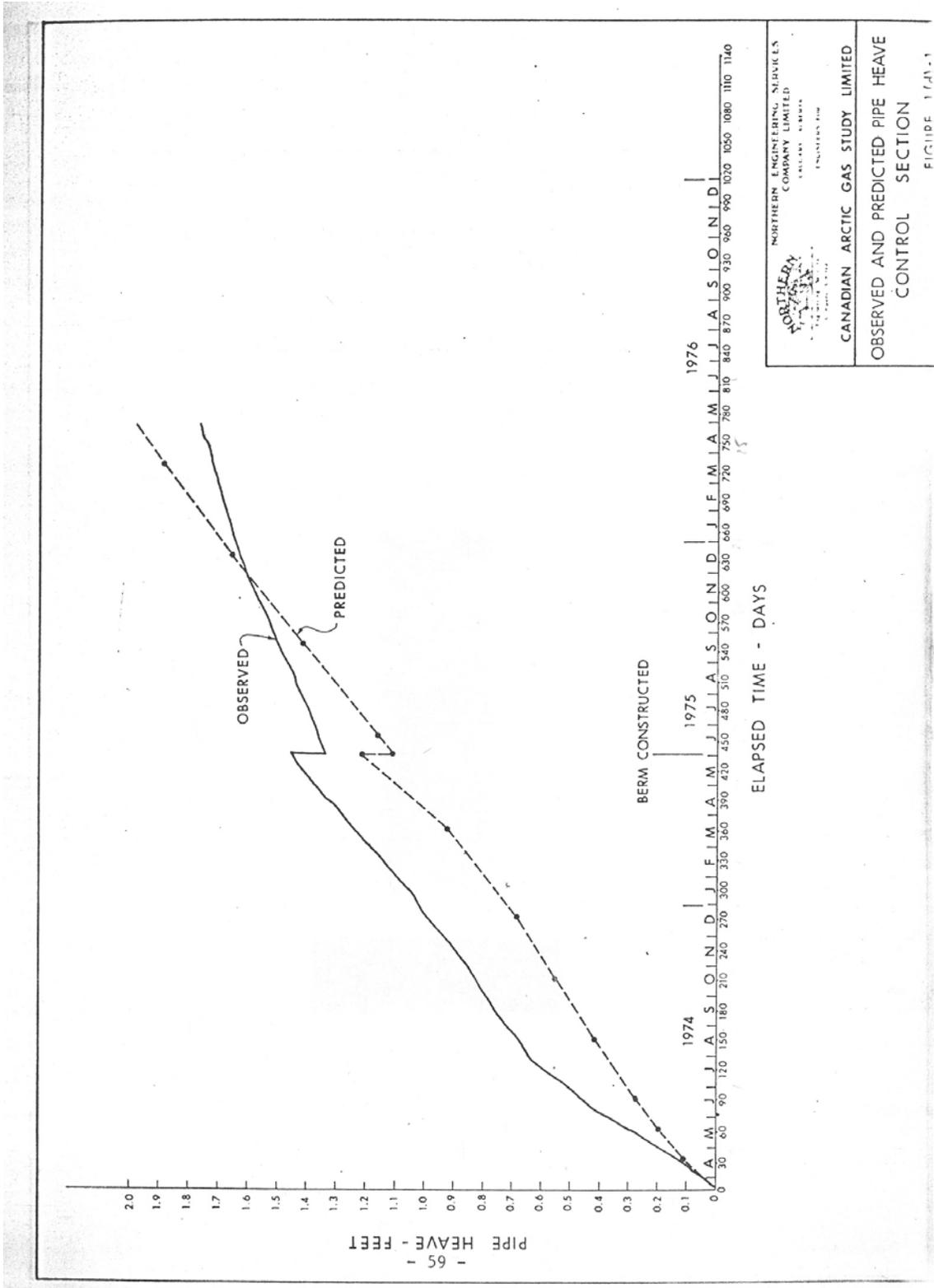
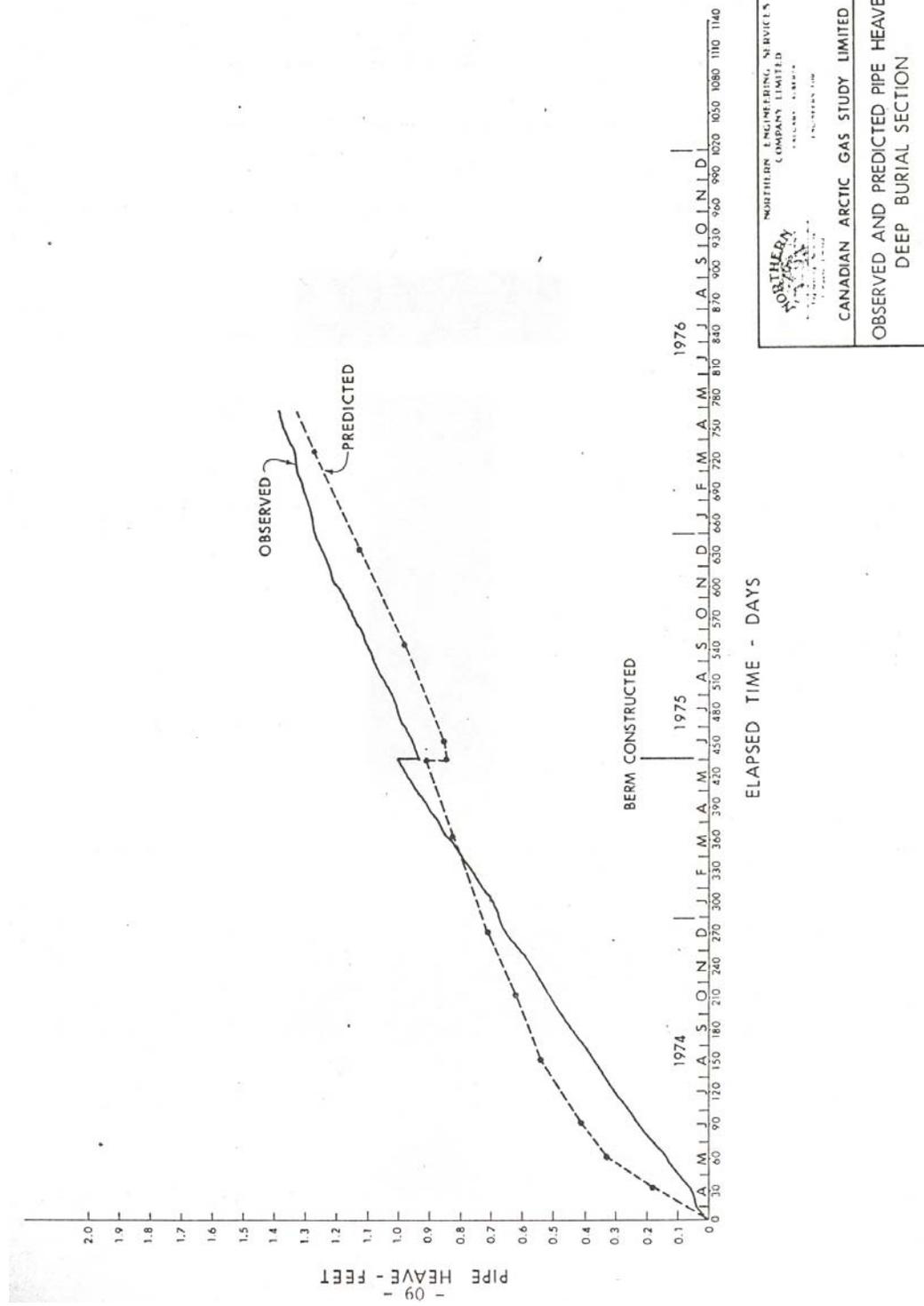


Figure 3 Calgary frost heave test facility — observed pipe heave and depth of frost below bottom of pipe

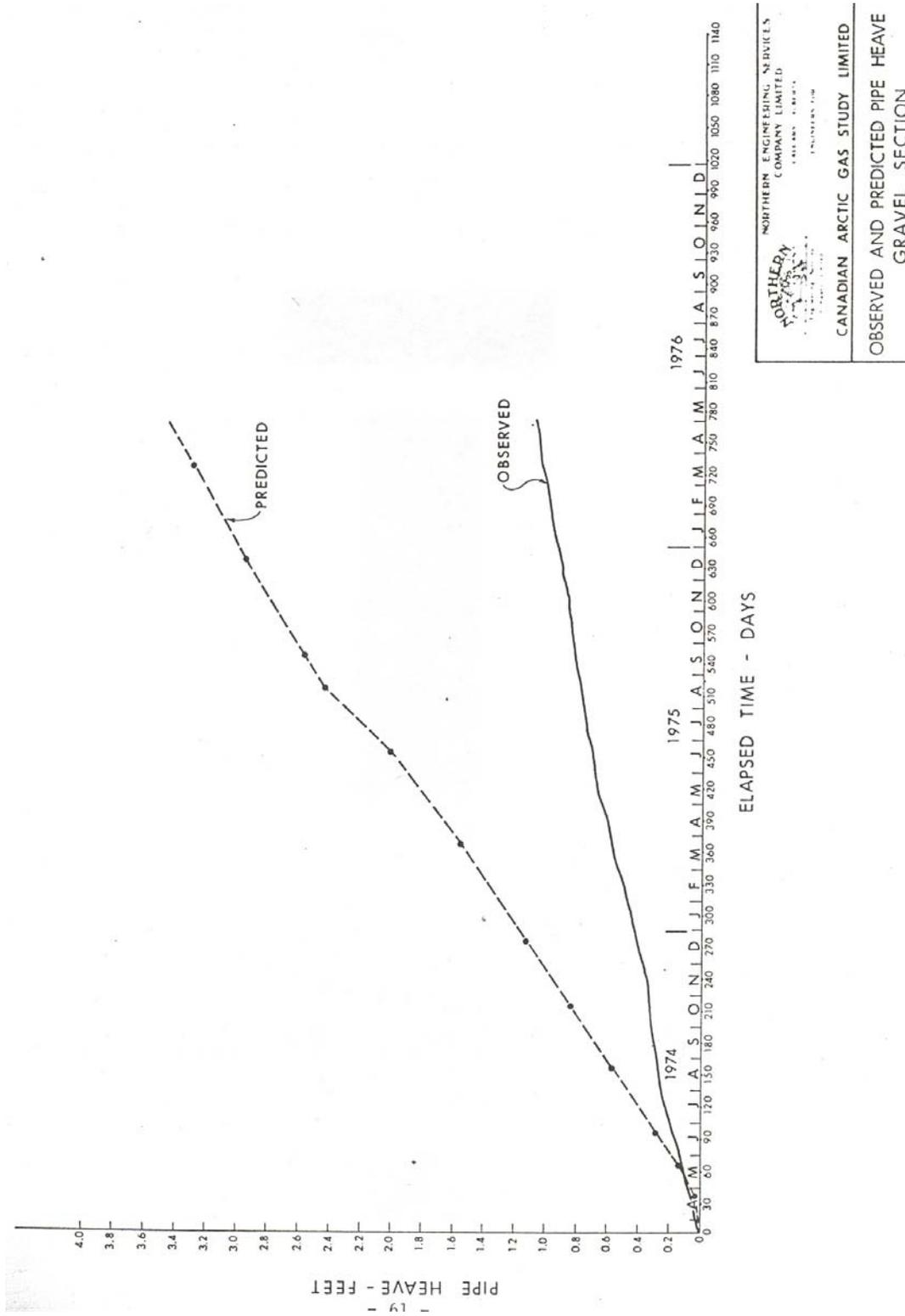
Summary of Test Results After Carlson et al 1981)



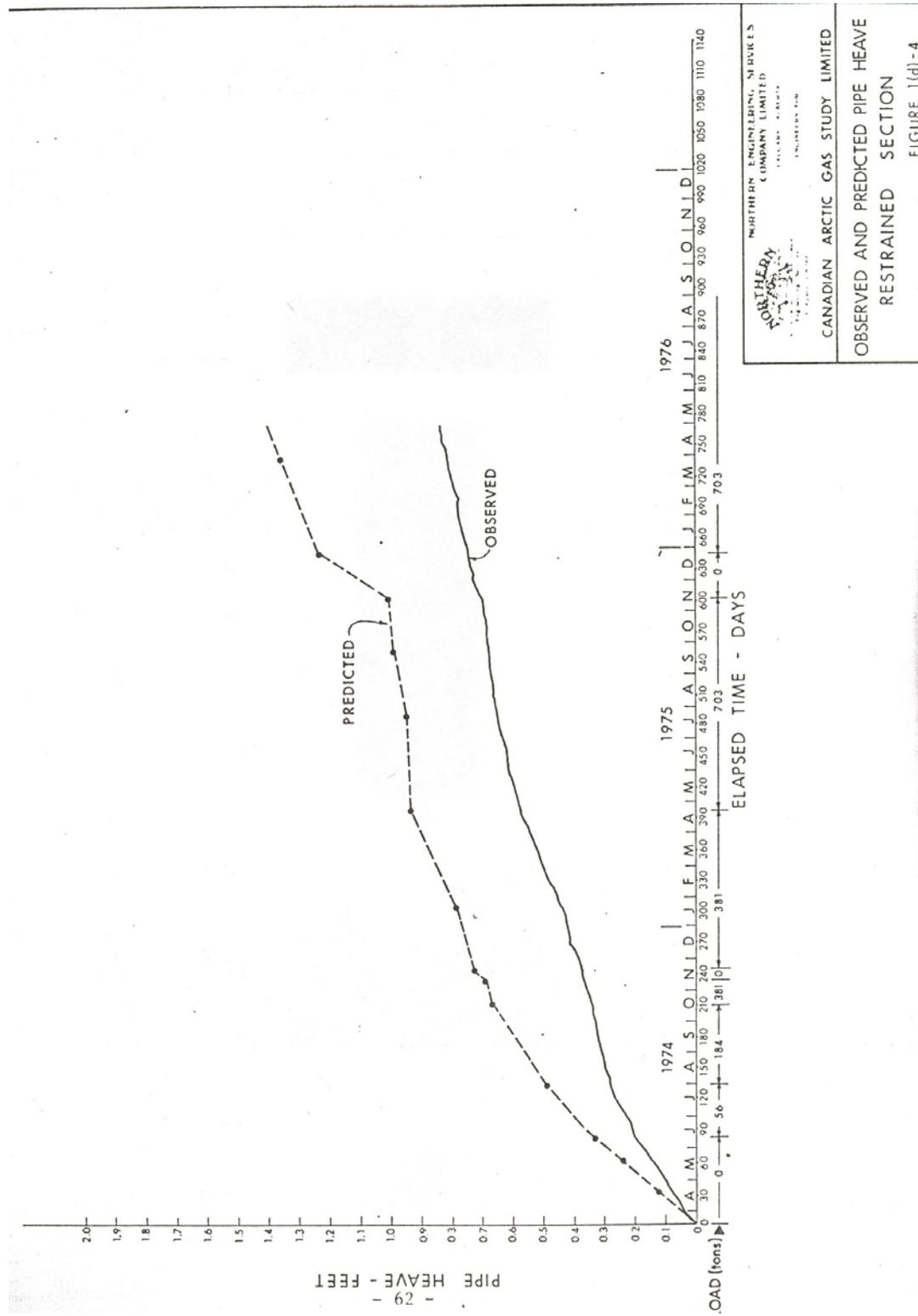
Pipe Heave – Control Section (After NES 1976)



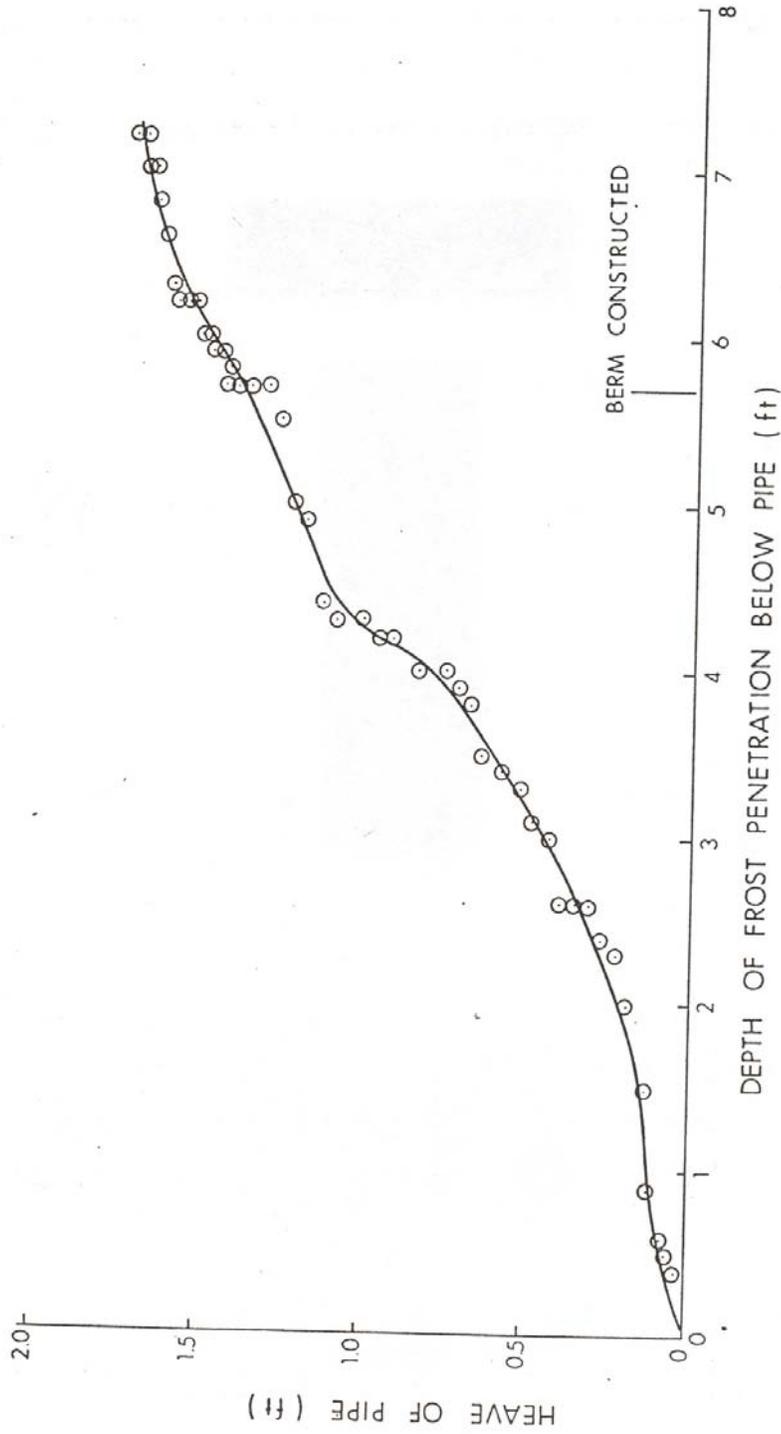
Pipe Heave – Deep Burial Section (After NES 1976)



Pipe Heave – Gravel Section (After NES 1976)



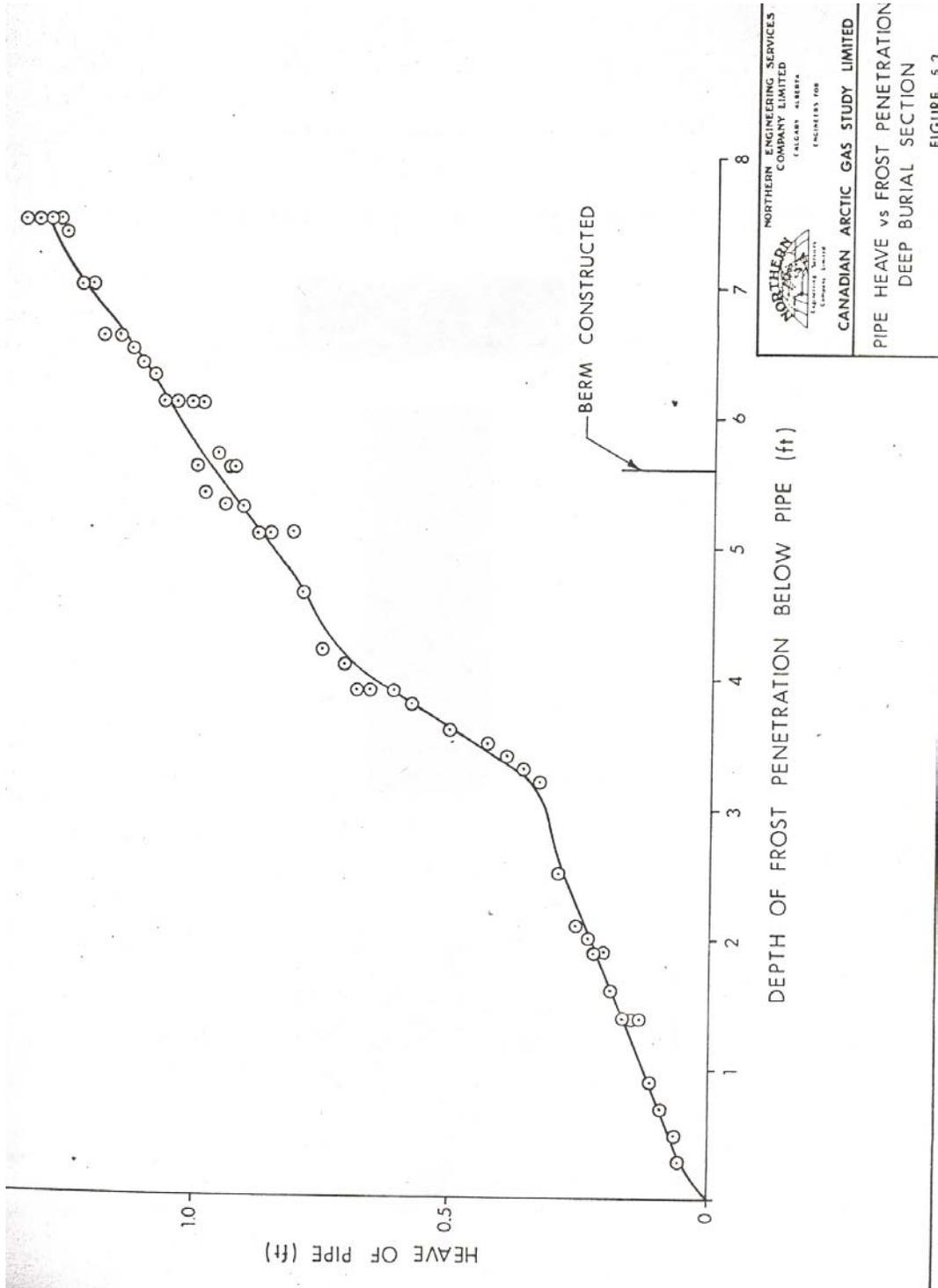
Pipe Heave – Restrained Section (After NES 1976)



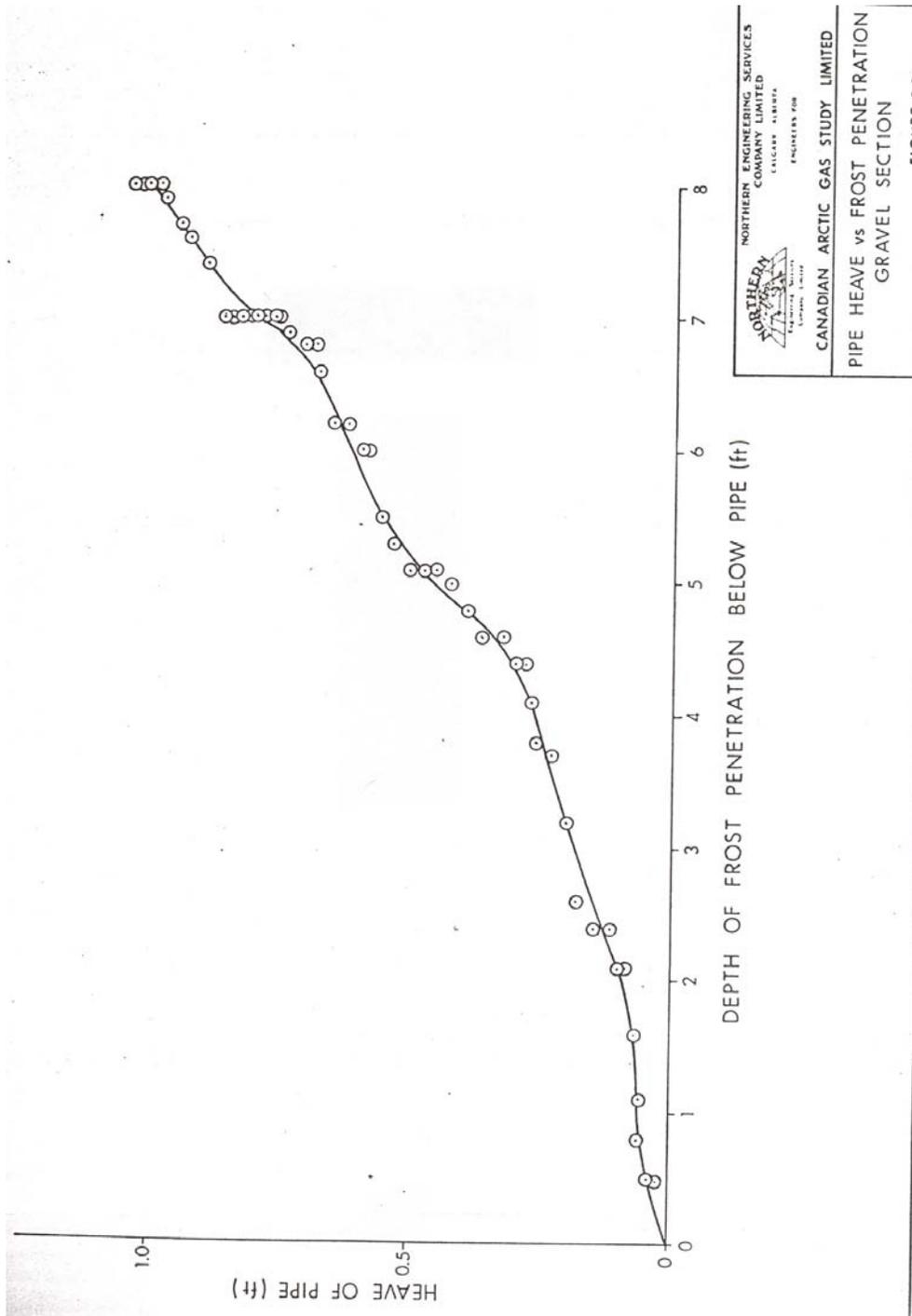
 NORTHERN ENGINEERING SERVICES NORTHWESTERN ENGINEERING SERVICES CALGARY ALBERTA ENGINEERS FOR	NORTHERN ENGINEERING SERVICES COMPANY LIMITED CALGARY ALBERTA ENGINEERS FOR
	CANADIAN ARCTIC GAS STUDY LIMITED PIPE HEAVE vs FROST PENETRATION CONTROL SECTION

FIGURE 6-1

Pipe Heave vs. Frost Penetration – Control Section (After NES 1976)



Pipe Heave vs. Frost penetration – Deep Burial Section (After NES 1976)



Pipe Heave vs. Frost Penetration – Gravel Section (After NES 1976)



Surface Effects Due to Pipe Heave (From JICA Library)

**Fairbanks 1 Frost Heave Test Facility**

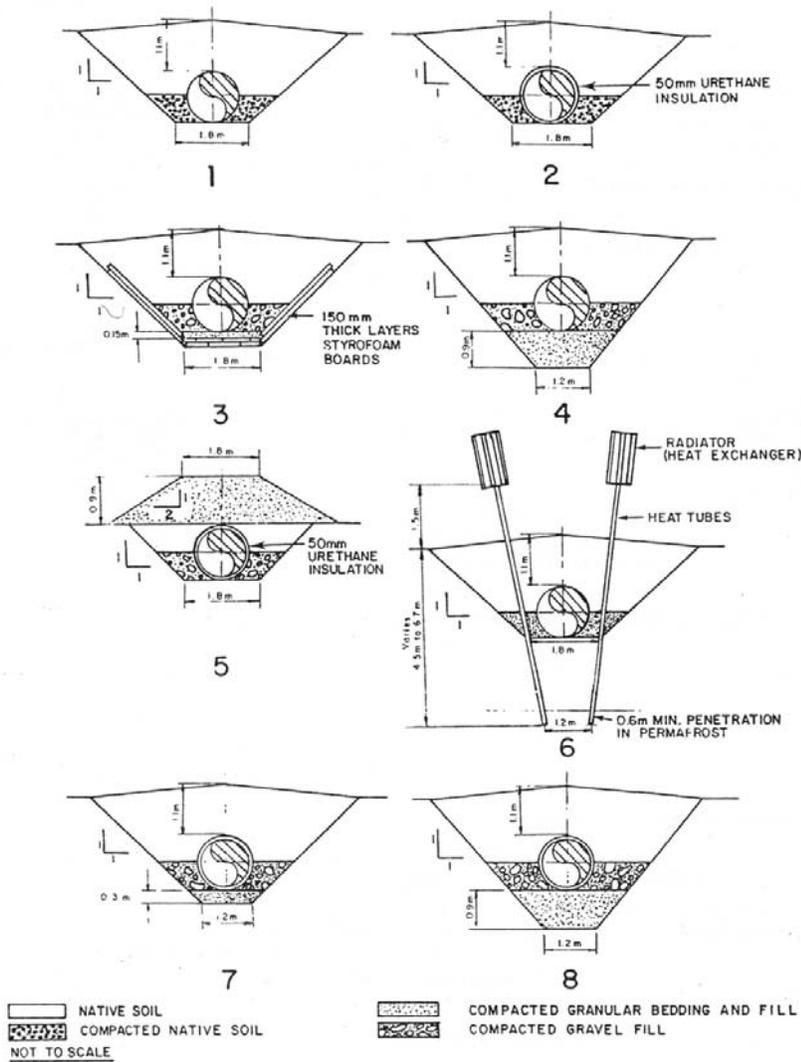
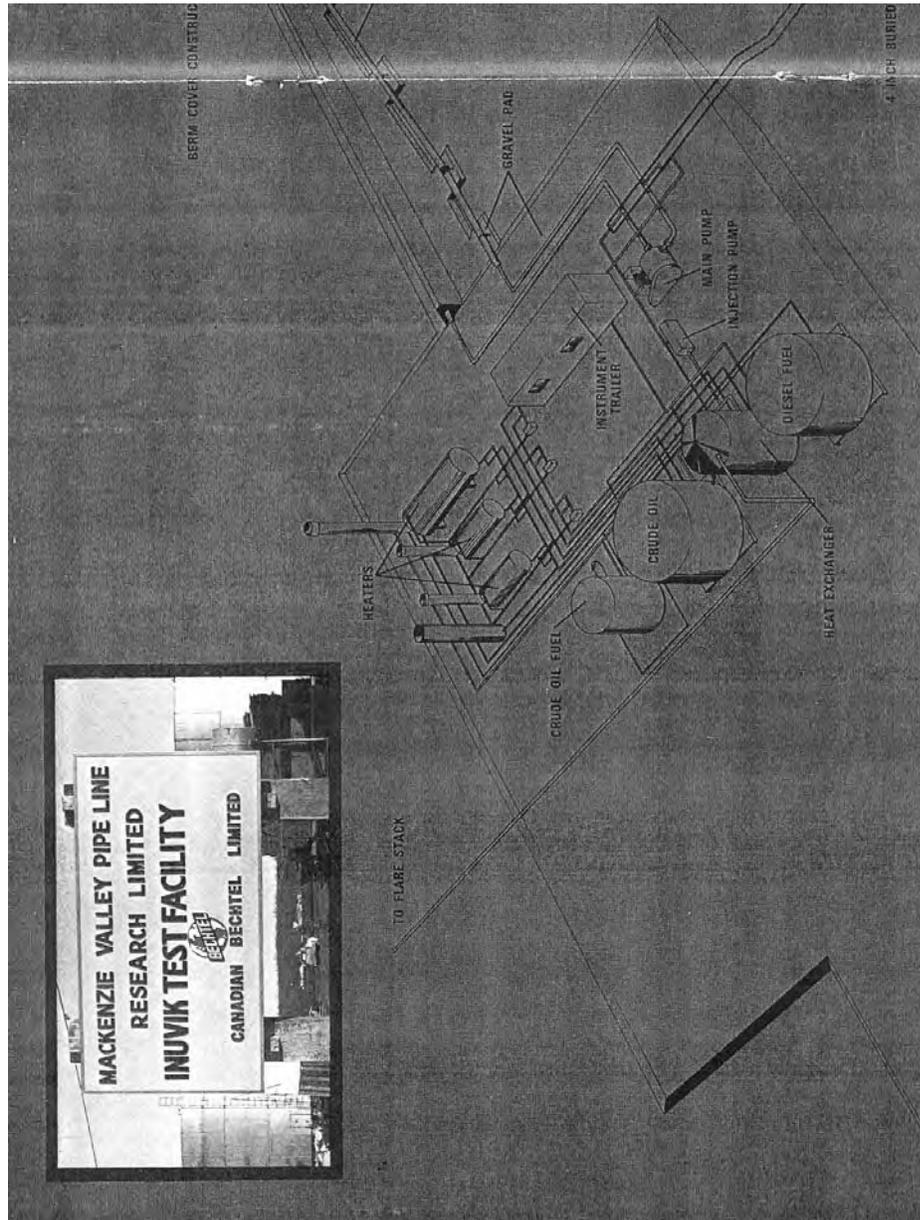


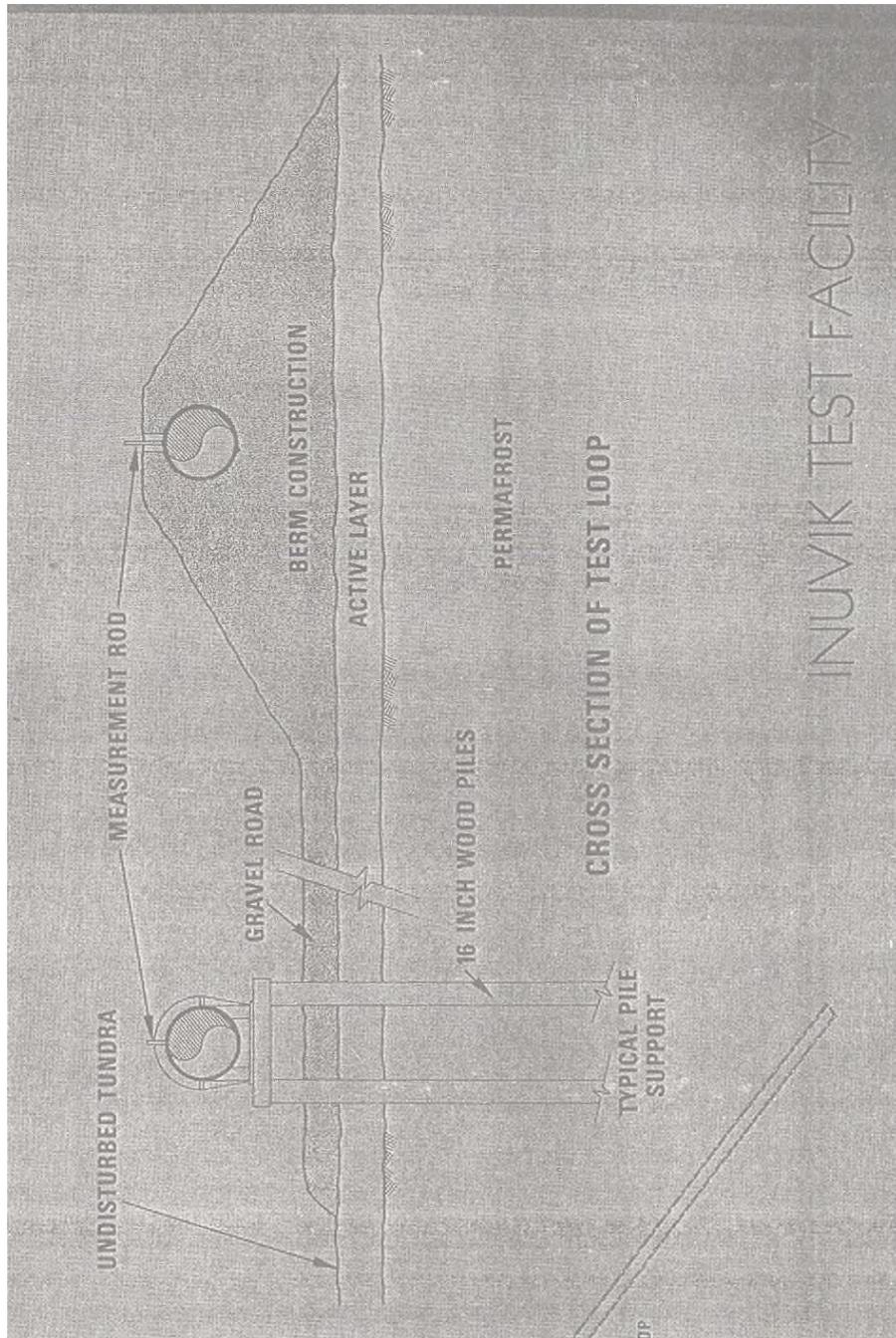
Figure 4 Ditch configurations, Fairbanks frost heave test facility

Test Pipe Burial Configurations (After Carlson 1985)

**Inuvik Hot Oil Test Facility**

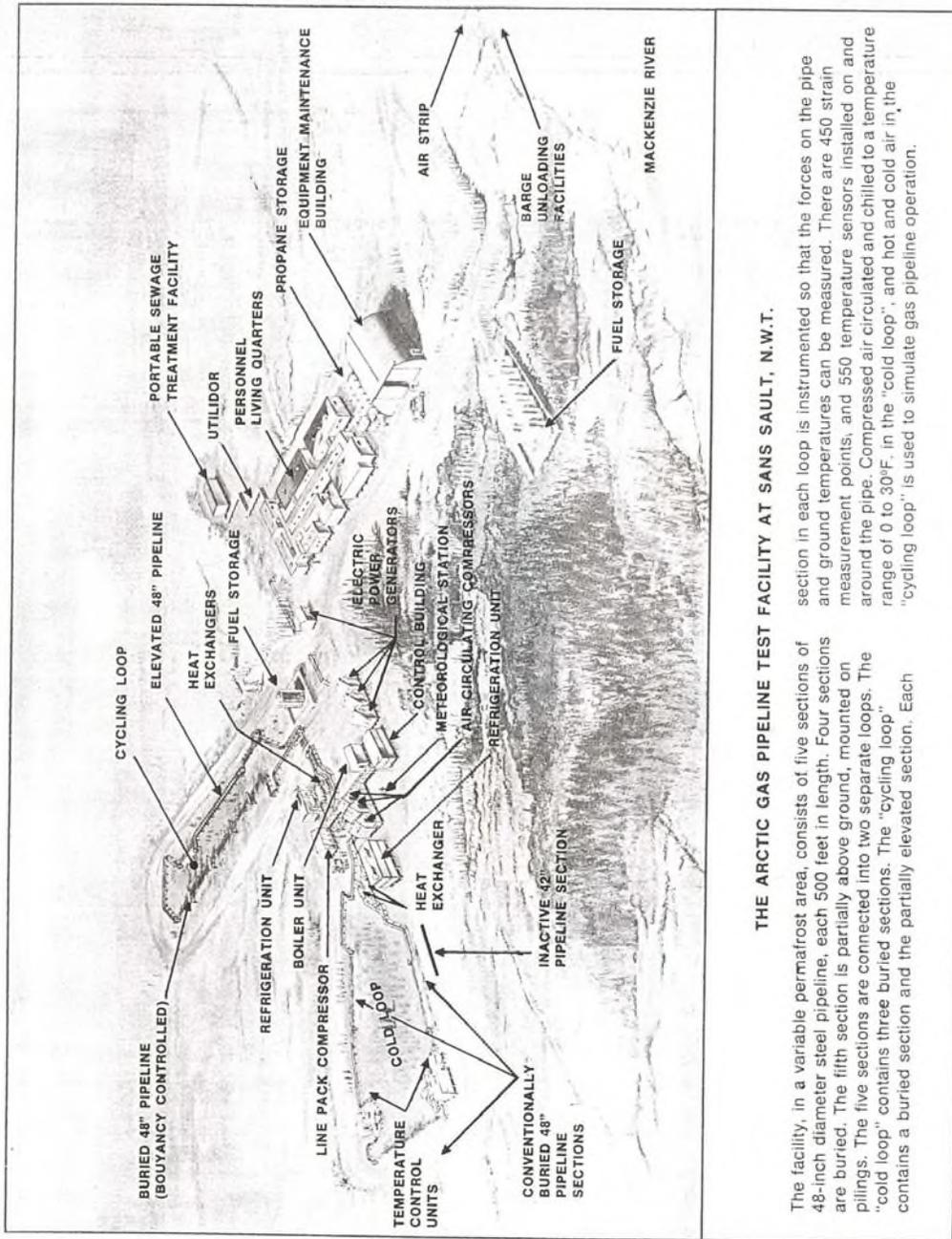


Test Facility Layout (After Research at Inuvik 1970)



Test Pipe Arrangement (After Research at Inuvik 1970)

**Mountain River / Sans Sault Rapids Frost Heave Test Facility**



Test Facility General Layout (After Walker 1973)

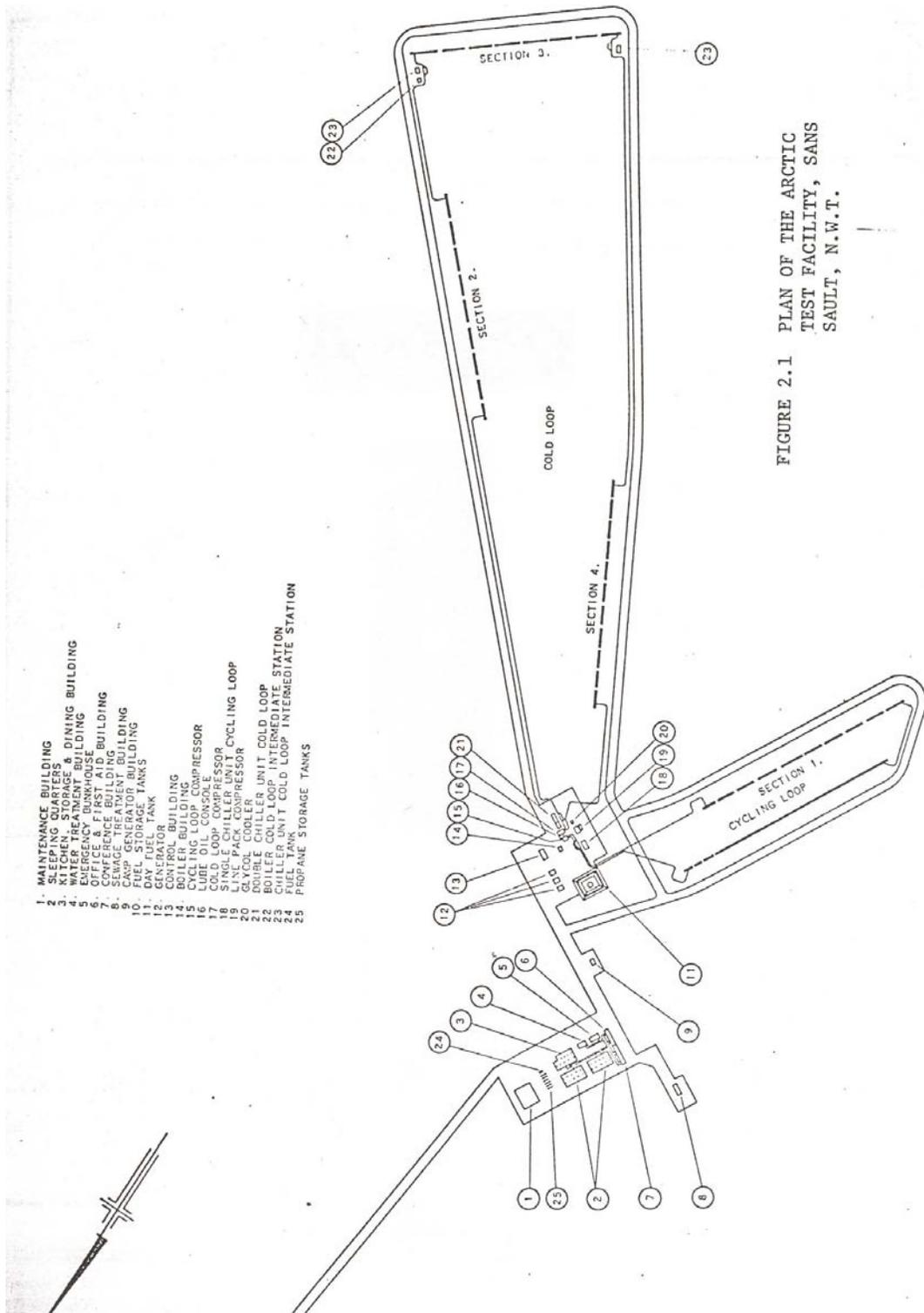
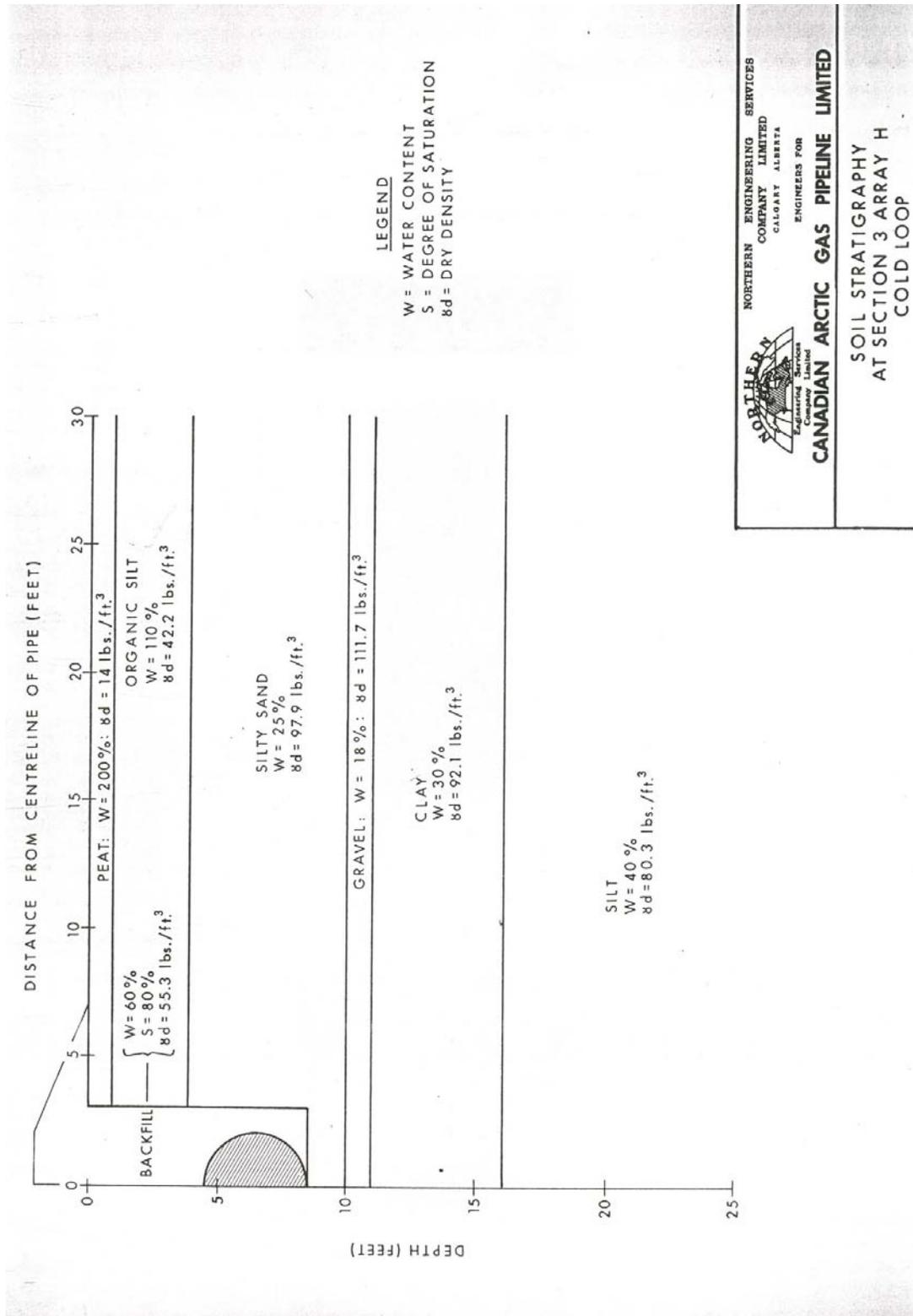
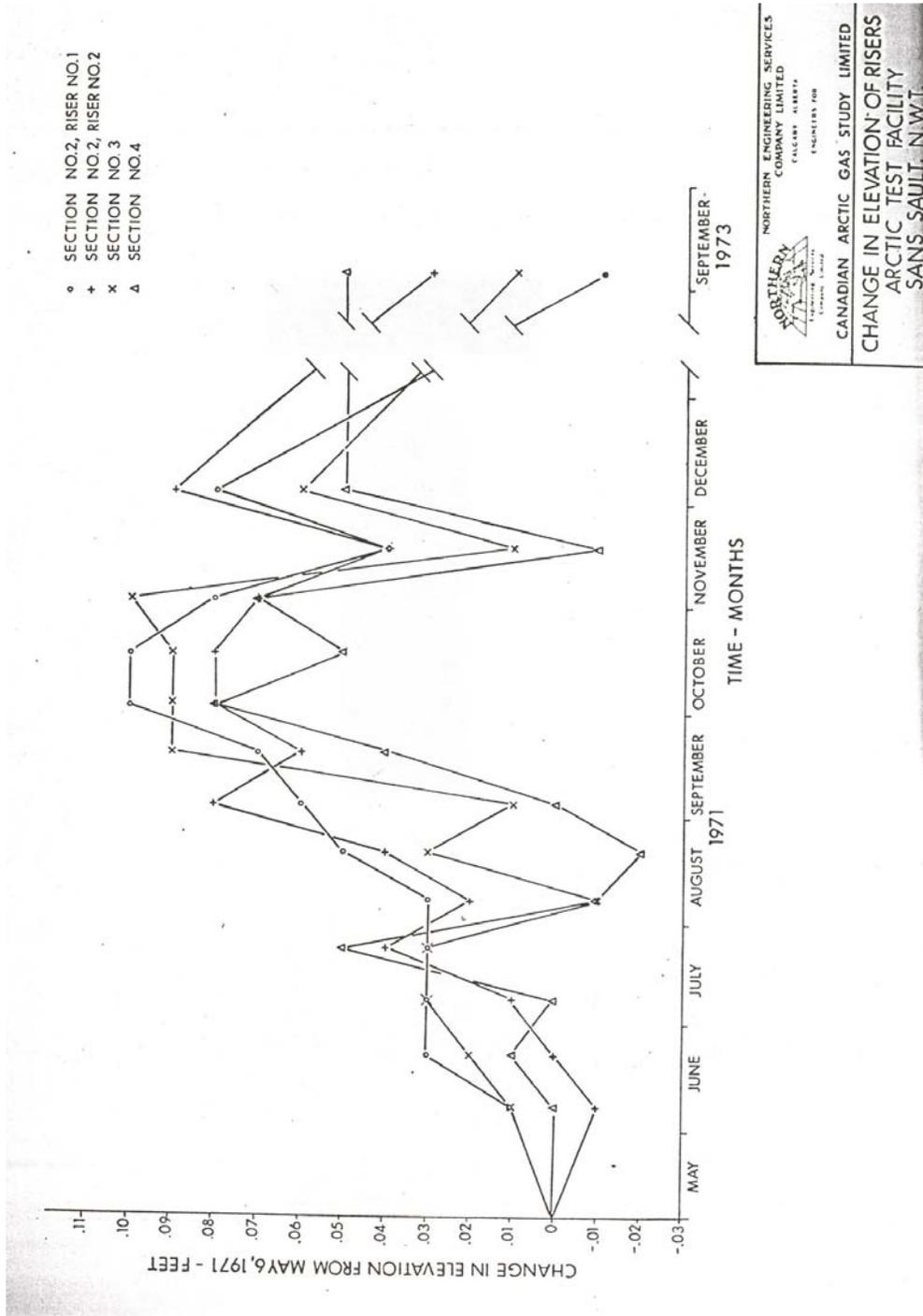


FIGURE 2.1 PLAN OF THE ARCTIC TEST FACILITY, SANS SAULT, N.W.T.

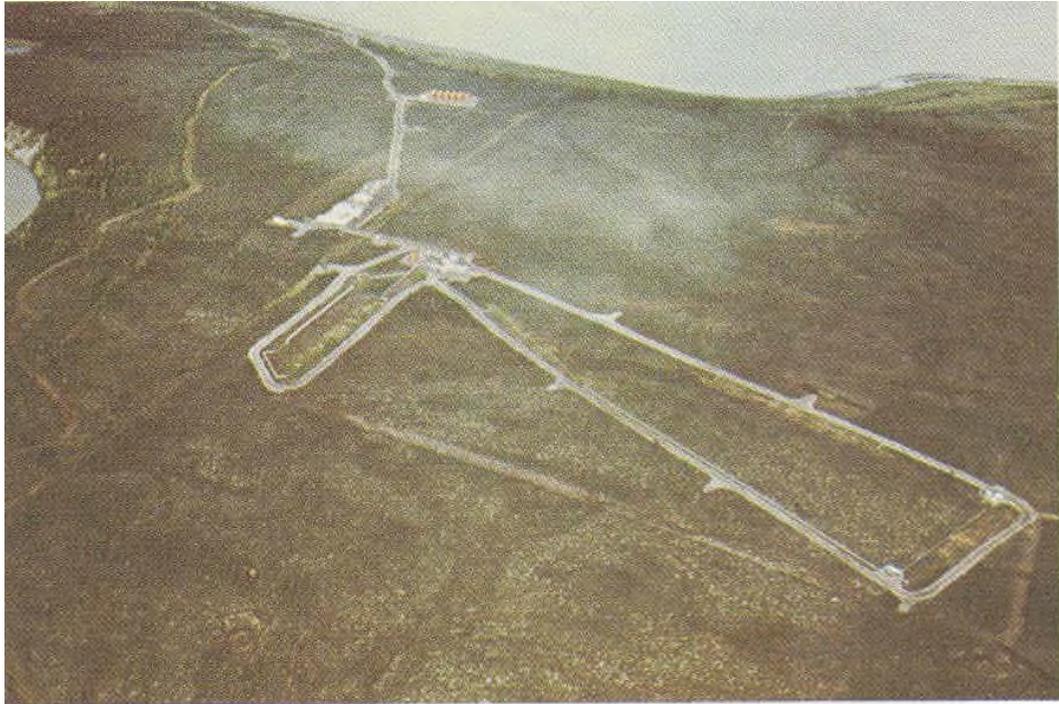
Test Facility Schematic Layout (After NES 1976)



Pipe Burial Arrangement – Cold Loop (After NES 1974)



Pipe Movement Measurements (After NES 1976)

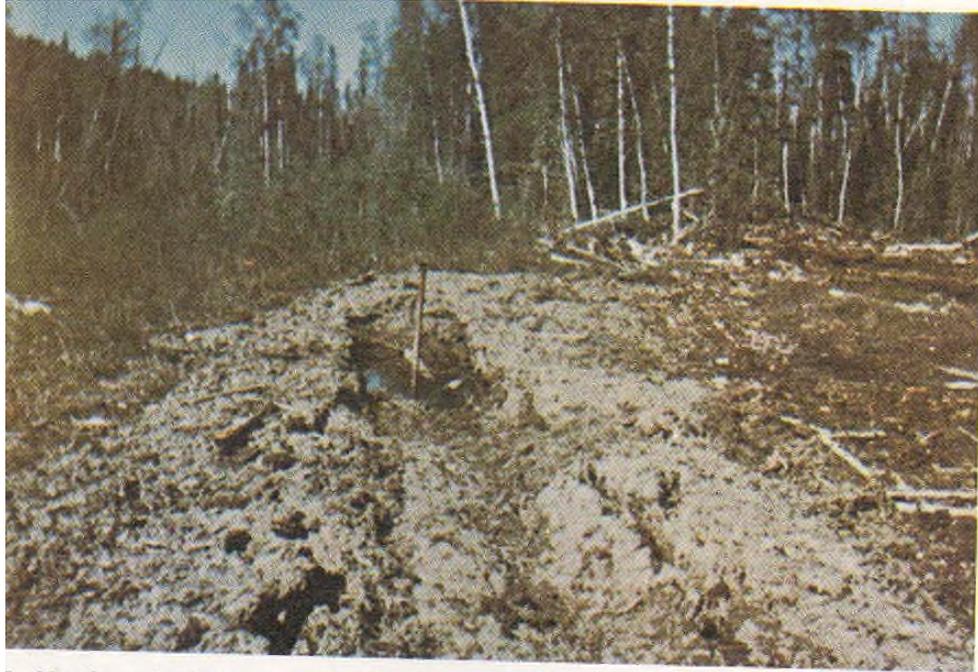


1. Aerial view of Sans Sault Arctic Test Facility. September 1973.

Arial View of Facility (From JICA Library)



Ditcher Tests (From JICA Library)

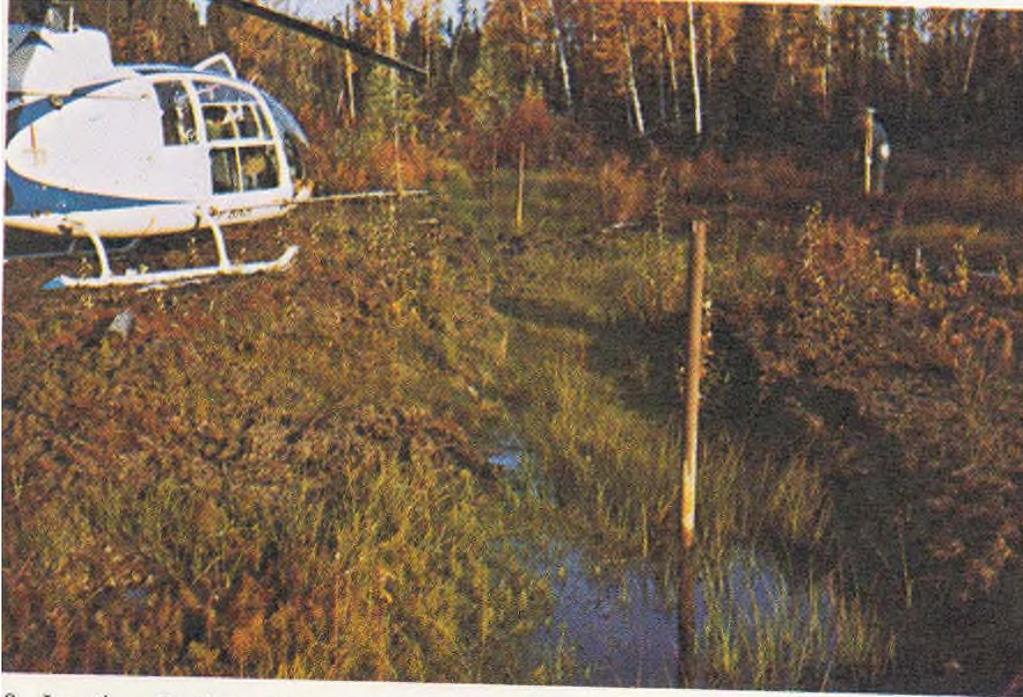


7. North end of Inactive Section No. 4, August 1971. Note subsidence along ditch line.

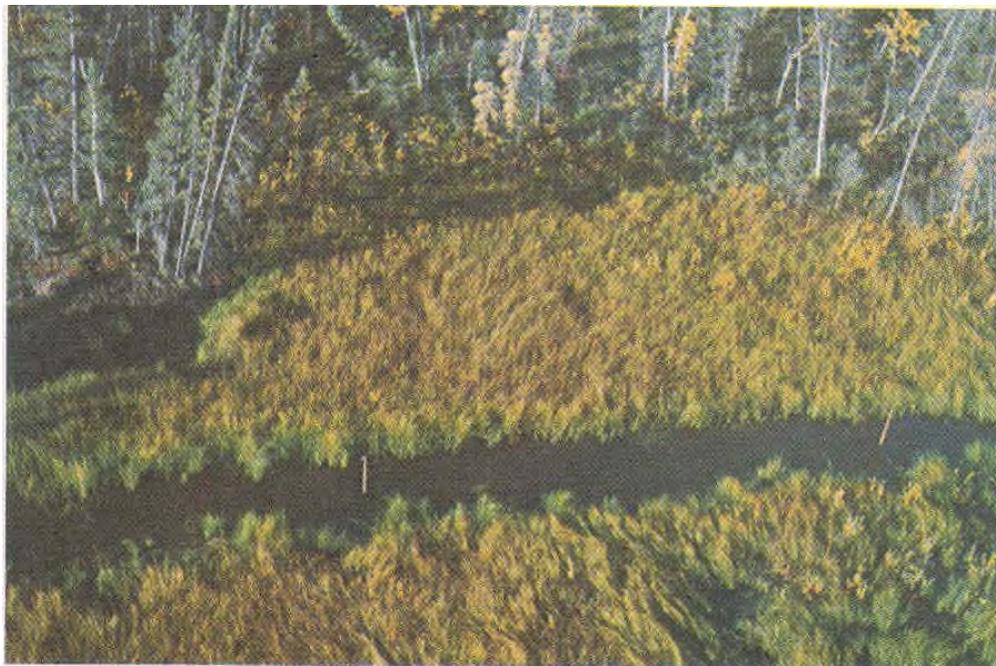


9. Inactive Section No. 5, August 1971. View from south end of site. Area around the test section is flooded each summer.

General Surface Conditions at Inactive Sections (From JICA Library)

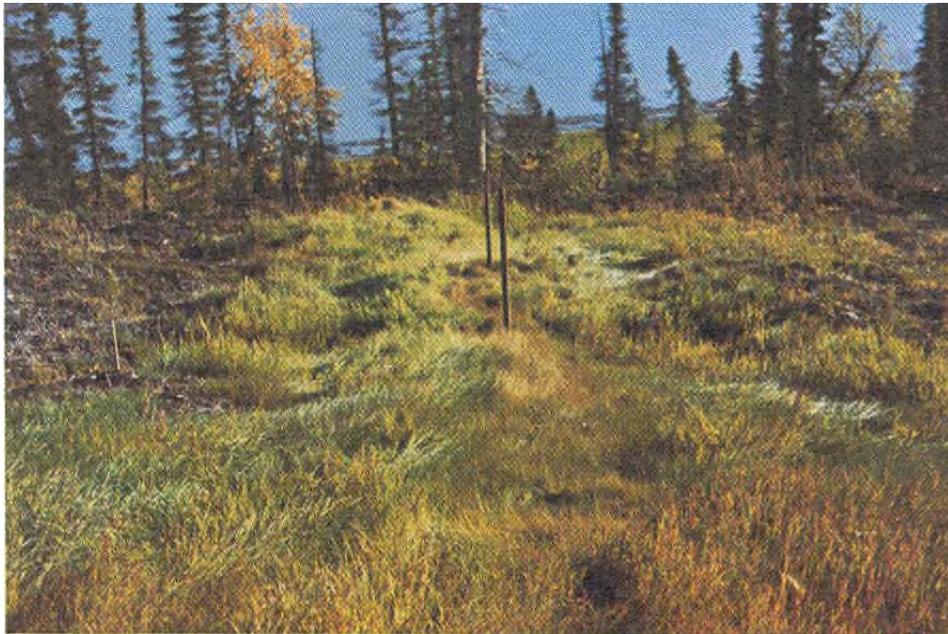


8. Inactive Section No. 4, September 1973. View from south end showing settlement along ditch line.



20. Aerial view of Inactive Section No. 5, September 1973.

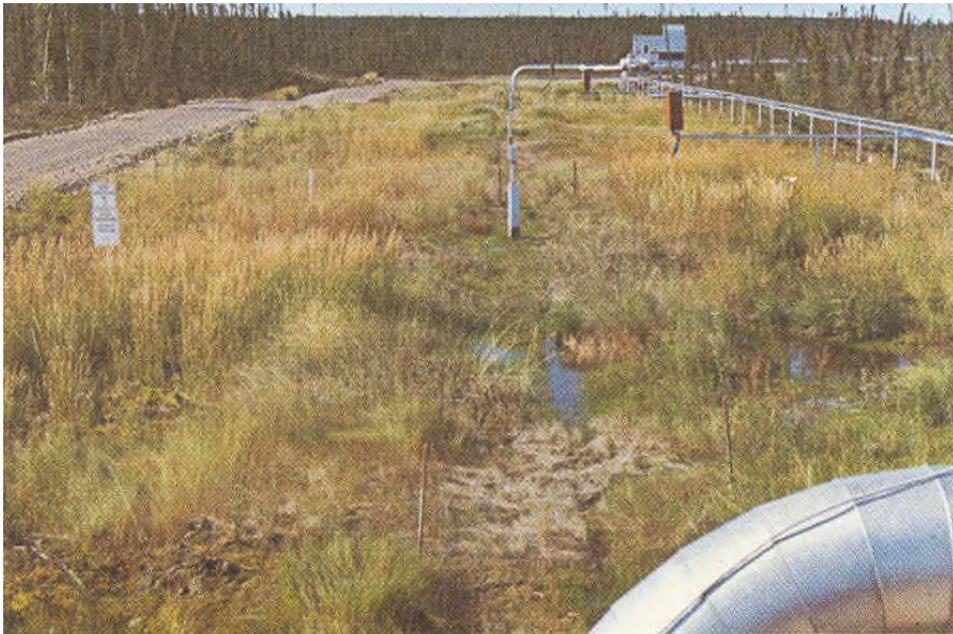
General Surface Conditions at Inactive Sections (From JICA Library)



General Surface Conditions at Inactive Sections (From JICA Library)



7. Cold Loop. View of Section 3 from west end, July 1971.

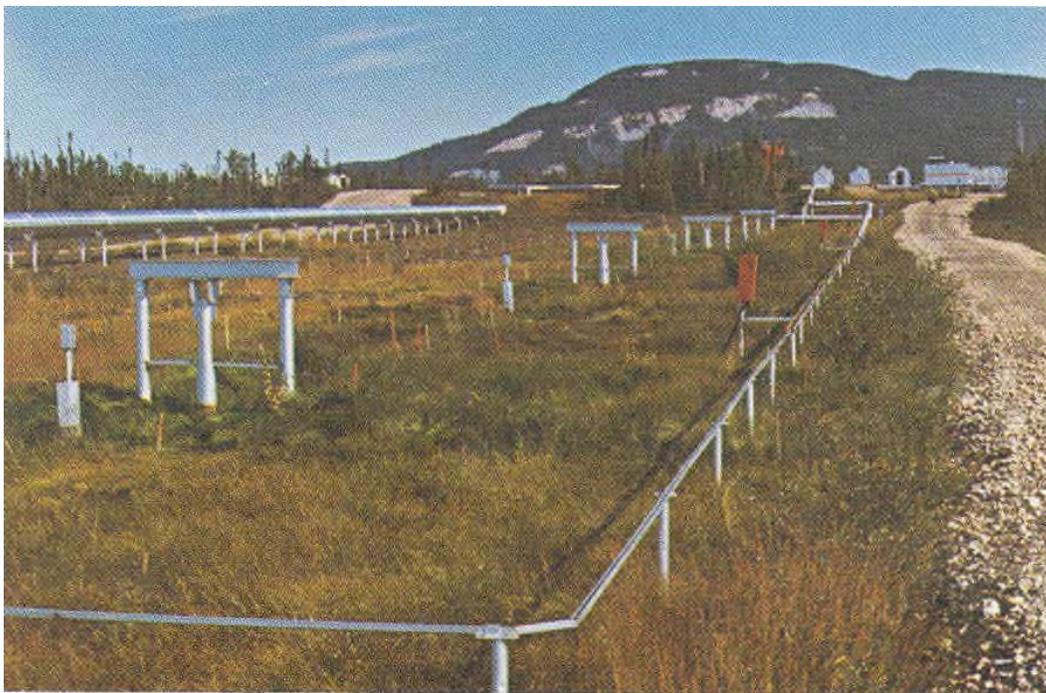


8. Cold Loop. View of Section 3 from east end, August 1973. Ground settlement evident from unpainted portion at the base of the strain gauge boxes.

Surface Conditions at Cold Loop (From JICA Library)



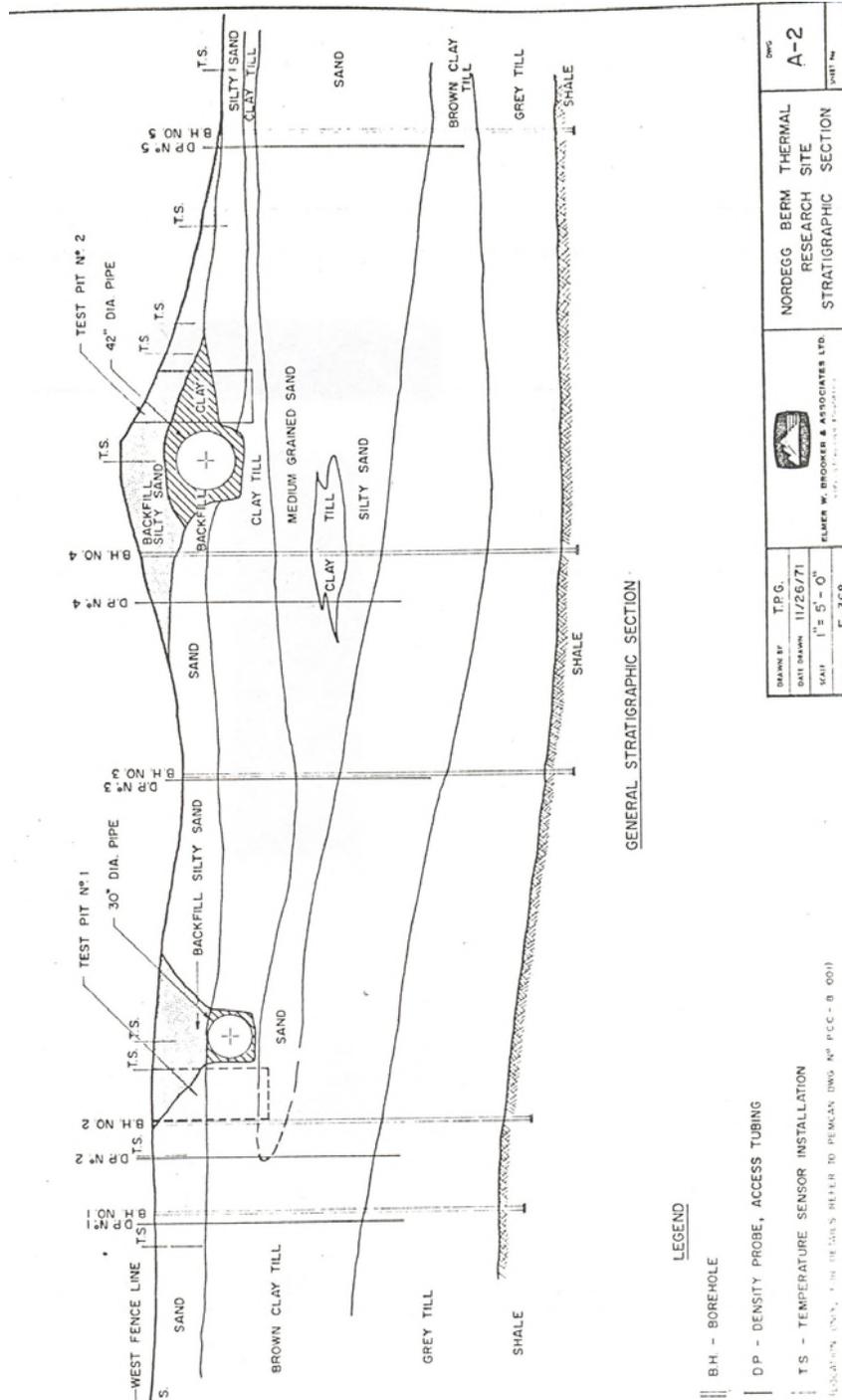
3. Cycling Loop. View from east end of Section 1, July 1971. Section 5 on the extreme right.



4. Cycling Loop. View from west end of Section 1, August 1973. Section 5 to the left.

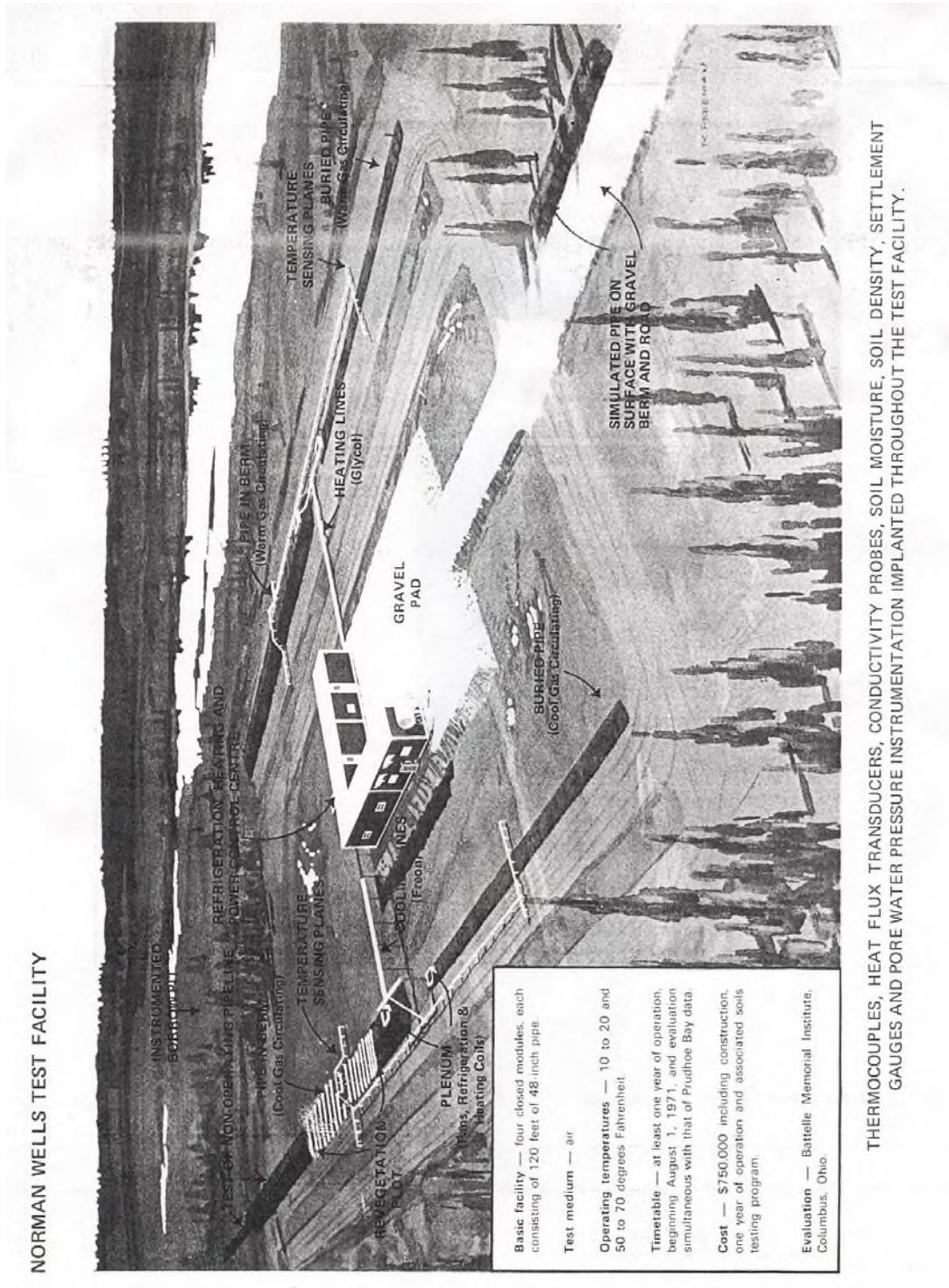
Surface Conditions at Cycling Loop (From JICA Library)

**Nordegg Chilled Gas Test Facility**



Pipe Burial Arrangement (After E W Booker & Associates 1971)

**Norman Wells Chilled Gas Test Facility**



NORMAN WELLS TEST FACILITY

**Basic facility** — four closed modules, each consisting of 120 feet of 48 inch pipe

**Test medium** — air

**Operating temperatures** — 10 to 20 and 50 to 70 degrees Fahrenheit

**Timetable** — at least one year of operation, beginning August 1, 1971, and evaluation simultaneous with that of Prudhoe Bay data

**Cost** — \$750,000 including construction, one year of operation and associated soils testing program.

**Evaluation** — Battelle Memorial Institute, Columbus, Ohio

THERMOCOUPLES, HEAT FLUX TRANSDUCERS, CONDUCTIVITY PROBES, SOIL MOISTURE, SOIL DENSITY, SETTLEMENT GAUGES AND PORE WATER PRESSURE INSTRUMENTATION IMPLANTED THROUGHOUT THE TEST FACILITY.

General Layout of Test Facility (After Walker 1973)

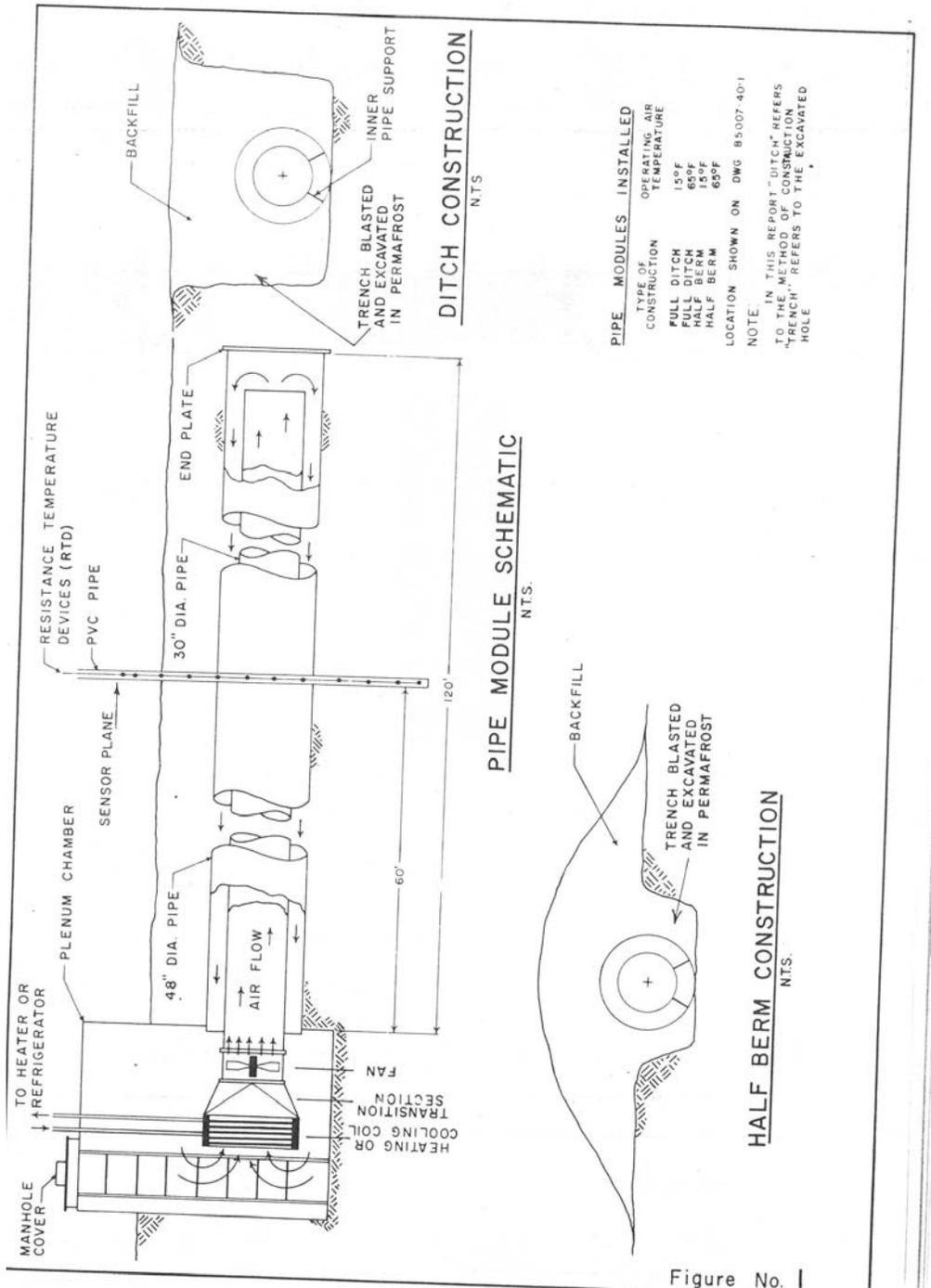
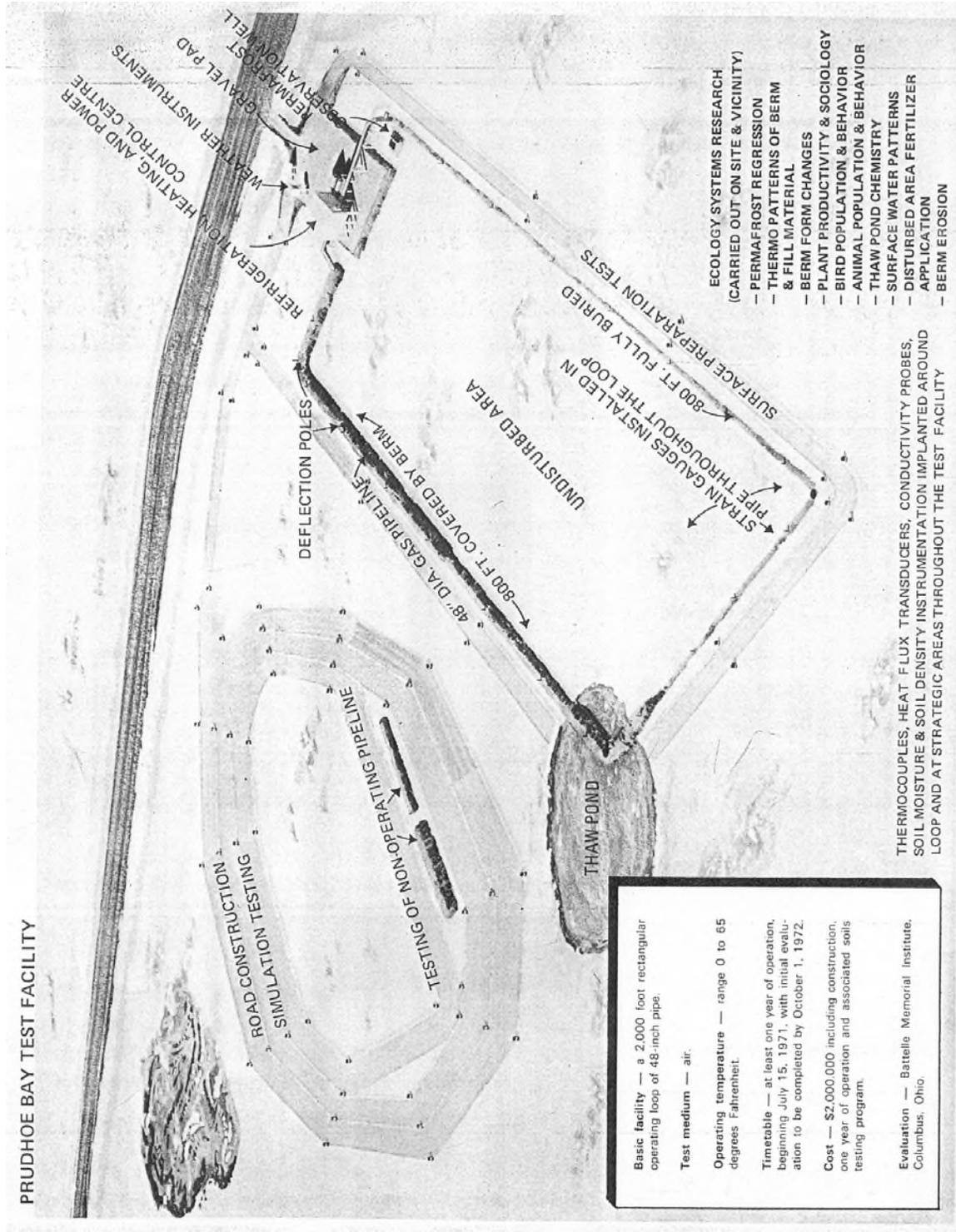


Figure No. 1

Pipe Burial Arrangement (After Pemcan Services 1972)

## **Prudhoe Bay Test Facility**



Test Facility Layout (After Walker 1973)

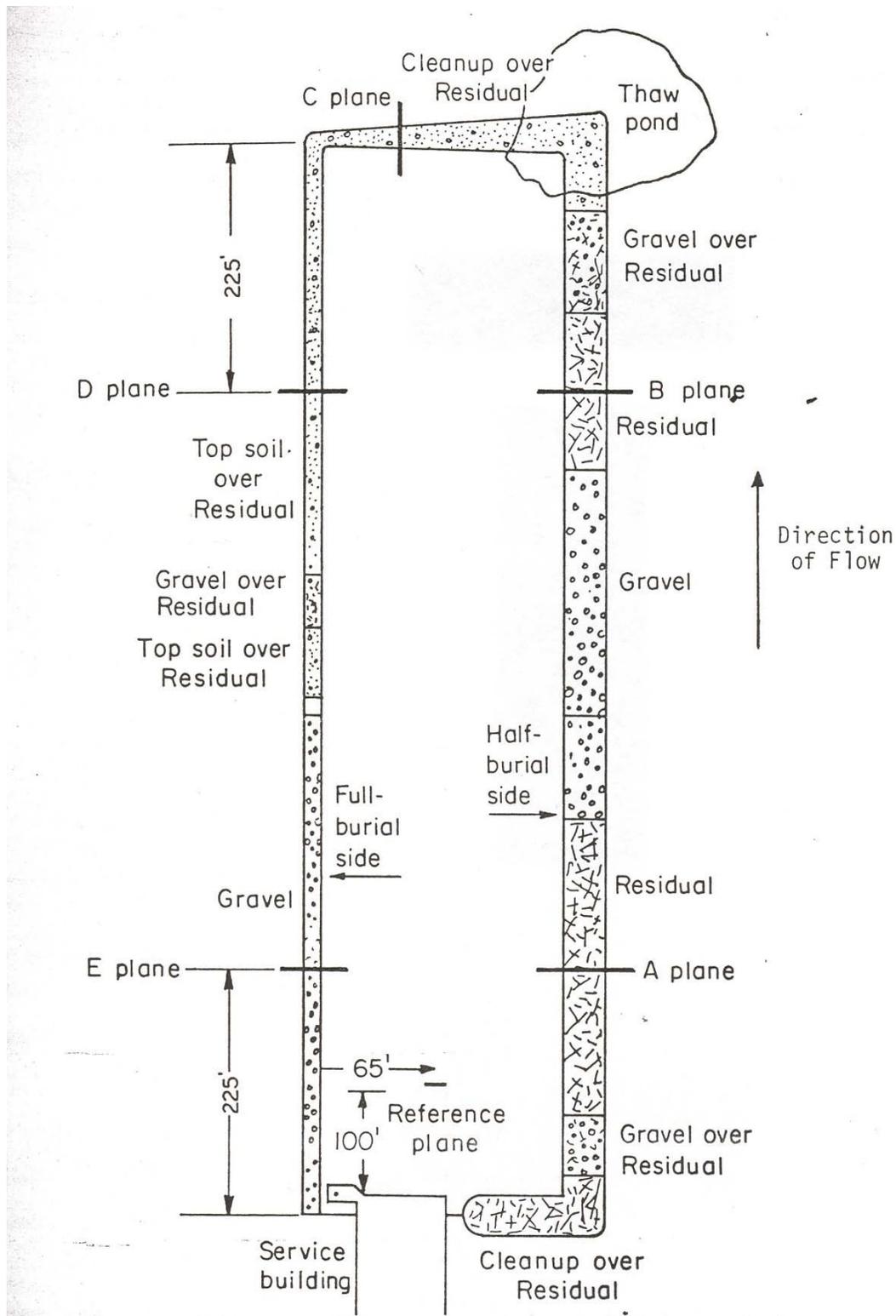
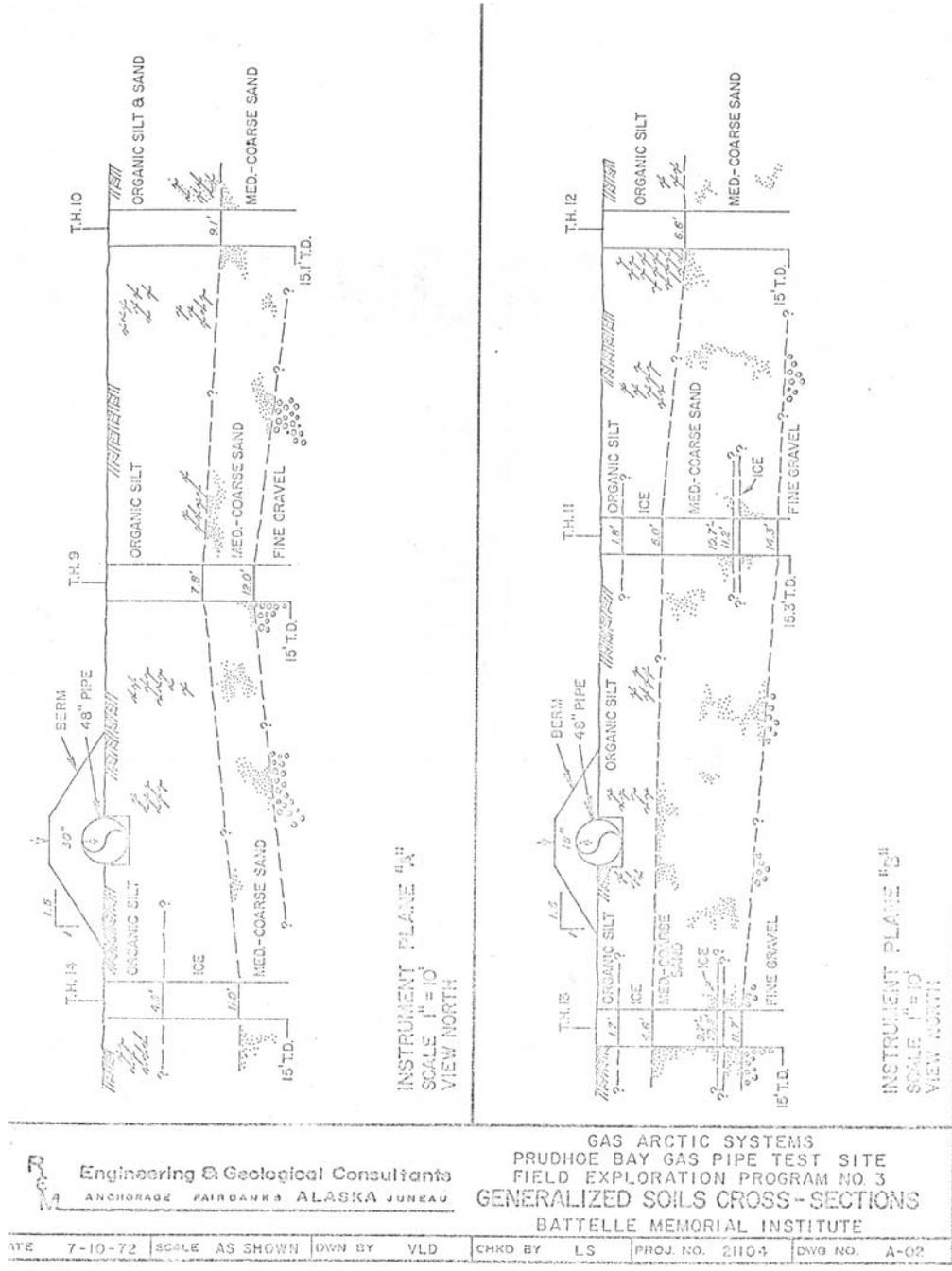


FIGURE 10. LOCATION OF THERMAL INSTRUMENTATION PLANES

Test Facility Layout (After Battelle Engineering 1972)



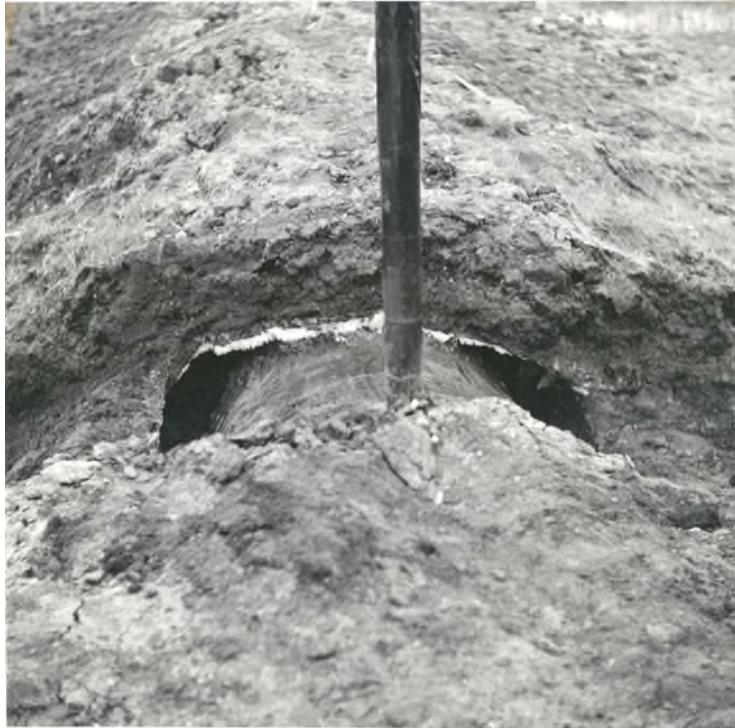
Soil Stratigraphy (After R&M Engineering 1972)



Surface Subsidence due to Partial Chilling Failure (From JICA Library)



Pipe Flotation due to Chilling Failure (From JICA Library)



Void Formation above Bermed Pipe Section (From JICA Library)

## **Quill Creek Test Facility**

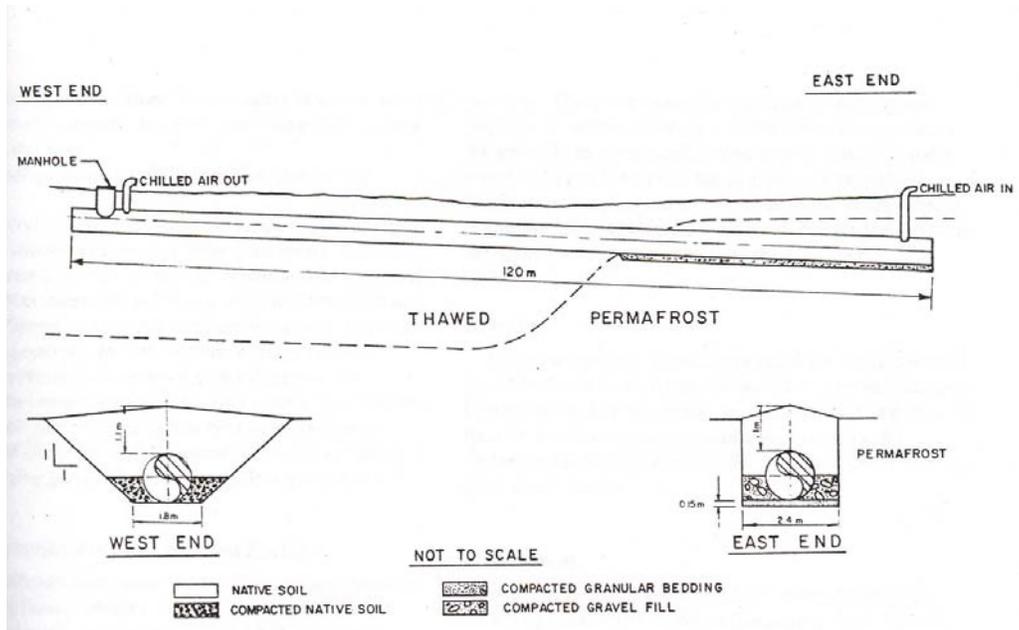


Figure 5 Interface test pipe. Fairbanks frost heave test facility

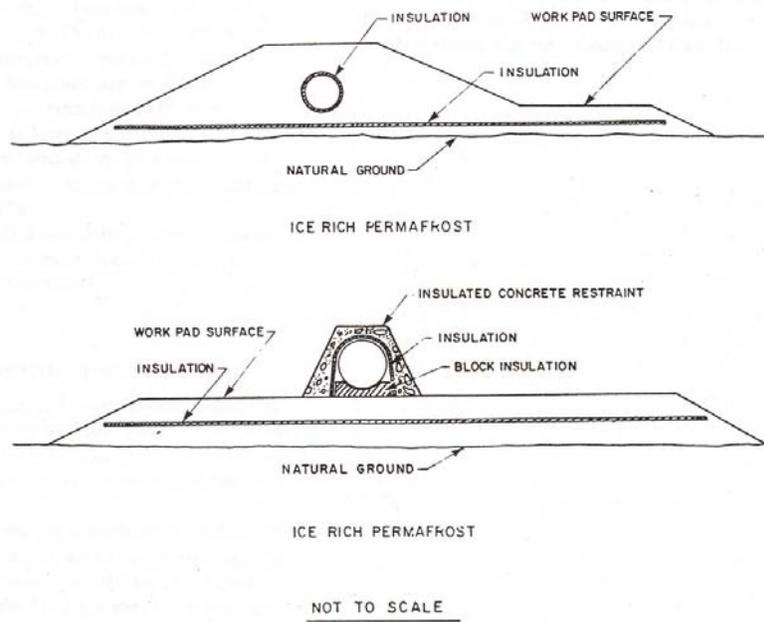


Figure 6 Thaw settlement design modes. Quill Creek test facility

Test Pipe Arrangement (After Carlson 1985)

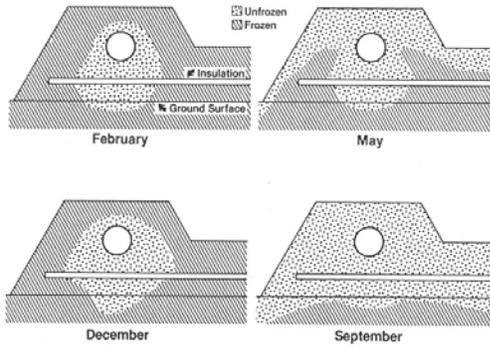


FIGURE 4 Thermal History. Uninsulated pipe in insulated embankment.

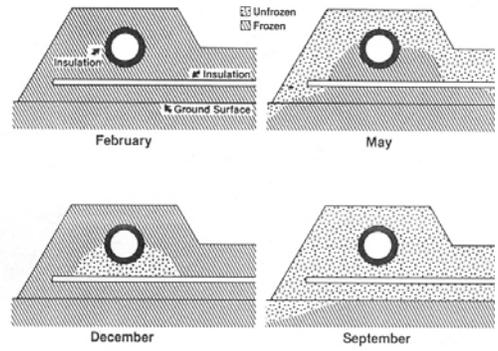


FIGURE 5 Thermal History - Insulated pipe in insulated embankment.

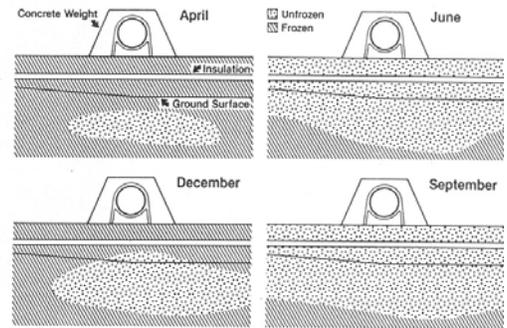
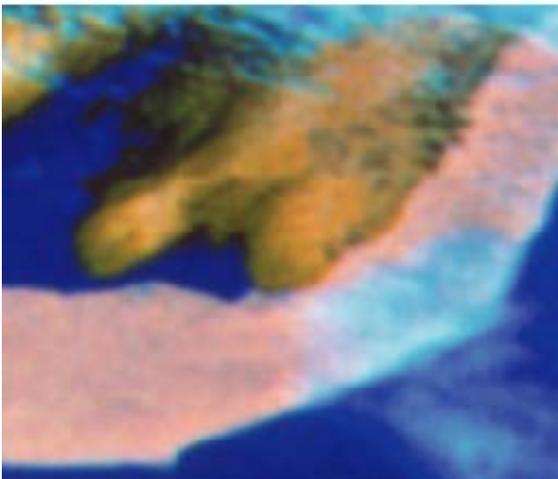
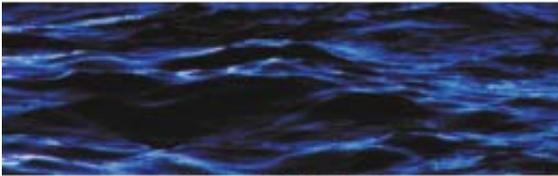


FIGURE 6 Thermal History. Concrete covered pipe on insulated gravel pad.

Pipe Sections – Thermal Effects (After Carlson & Butterwick 1983)

## **Part 4.**

**Review of centrifuge testing applicability to frost heave, by C-Core, St John's.**



# REVIEW OF CENTRIFUGE TESTING APPLICABILITY TO FROST HEAVE

C-CORE Contract Report  
R-03-094-285 v3.0

June 2004



# **Review of Centrifuge Testing Applicability to Frost Heave**

## **Final Report**

### **Prepared for:**

Geological Survey of Canada

### **Prepared by:**

C-CORE

### **C-CORE Report**

R-03-094-285 v3.0  
June 2004



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Jack Clark, J.I. Clark & Associates  
Stuart Haigh, Cambridge University

## EXECUTIVE SUMMARY

This review summarizes the applicability of centrifuge technology to northern pipeline frost heave design issues and presents a summary of results of centrifuge modeling of frost heave to date, especially with relation to arctic pipelines. An independent opinion of centrifuge technology and its applicability to frost heave is also presented.

Over the past three decades, centrifuge modeling has become a widely accepted tool for the prediction of the behavior of soil-structure systems. Centrifuge modelling because of reduced scale, accelerated timeframe for controlled testing and cost effectiveness provides a unique opportunity for use in the prediction of frost heave and the design development for arctic pipelines. There are many coupled factors controlling the system response, such as geothermal conditions, hydrogeological conditions, confining stress variation, soil stress-strain behaviour, heat transfer, and pore water migration. Most of these factors are reasonably modelled in a centrifuge test. The engineering insight provided by such tests can be extremely valuable, especially with an appreciation of the modeling issues, which could distort the results.

If the scaled responses of two model tests at different scales are similar, then confidence is increased that these physical simulations are representative of full-scale conditions. Such modelling of models of one dimensional frost heave has shown that factors such as frost heave, frost penetration and heave rate do appear to scale correctly in a centrifuge model test. These models also showed good repeatability of results. This modelling of models technique should be used to validate pipe response to frost heave, coupled with tests to demonstrate repeatability of results.

Comparisons made between centrifuge model results and those from full-scale pipeline frost heave testing undertaken at the Calgary test site revealed similar behaviour patterns with respect to heave displacements and time, and a similar thermal response to the prototype conditions was also observed. The substantial reduction of heave rate due to increased pressure on the freezing front as the frost bulb grows was replicated. The circumferential ice lense pattern around the model pipe was consistent with observations from full-scale pipes and laboratory tests.

A semi-empirical design method is emerging, from current centrifuge model tests, which includes a relationship between rate of heave and pressure on the freezing front. The centrifuge model test program should be expanded through a parametric study to include for example consideration of different pipe geometries, burial configurations, soil types, and geothermal and hydro geological conditions. The program can also evaluate heave mitigation strategies and pipe soil interaction through, for example, discontinuous permafrost.



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## 1 OBJECTIVE

This review summarizes the applicability of centrifuge technology to northern pipeline frost heave design issues and presents a summary of results of centrifuge modeling to date of frost heave, especially with relation to arctic pipelines.

It also evaluates the contribution that centrifuge testing has made to the understanding of frost heave and frozen soil/pipe interaction, its character, mechanisms, rate and probable effects on a variety of soil types. The discussion considers the limitations and advantages of this type of testing along with a comparison of the results of full-scale tests and numerical modelling. There are no operating large diameter chilled pipelines in existence against which to extend this comparison. An assessment and comments on the future applicability of this type of testing for the validation of frost heave theory, prediction of frost heave and the design and operation of buried chilled pipelines, specifically for a Mackenzie Valley Pipeline is included.

An independent opinion of centrifuge technology and its applicability to frost heave was obtained from Dr. Stuart Haigh of Cambridge University as presented in Appendix A.

## 2 CENTRIFUGE MODELLING

Centrifuge modelling is a useful tool when modelling gravity-dependent phenomena in geotechnical systems, Schofield (1980) & Murff (1996). Centrifugal acceleration is used to simulate increased gravity and allows for correspondence of stress fields between model and full-scale, permitting accurate modelling of geotechnical and other gravity-dependent phenomena. Such modelling has regularly increased general understanding, and permitted calibration and verification of numerical and theoretical models of full-scale situations, Taylor (1995).

Centrifuge modelling has recently been used to replicate the full-scale pipeline frost heave testing undertaken in the 1970s and 80s in support of northern gas pipeline applications, eg. Clark & Phillips (2003). Centrifuge modelling because of reduced scaling, accelerated time frame for testing and cost effectiveness provides a unique opportunity for use in the prediction of frost heave and the development designs for arctic pipelines.

The geotechnical centrifuge modelling technique accounts for the stress-dependent behaviour of soils. Soil models placed at the end of a centrifuge arm are rotated to achieve an inertial radial acceleration field, which replicates Earth's gravity but at a higher level. If the same soil is used in both the model and prototype and the soils both have similar stress histories, then soil stress similarity is correctly modelled. When the soil model is subjected to an accelerated inertial stress field of  $N$  times Earth's gravity, the vertical stress at depth  $h_m$  in the model will be equal to the prototype vertical stress at soil depth  $h_p$  (where  $Nh_m = h_p$ ). This is the basis of centrifuge modelling and the associated scaling laws, that stress in the model and prototype are equal at a homologous point by accelerating a model of scale 1: $N$  to  $N$  times Earth's gravity ( $g$ ).

## 2.1 Frost Heave Issues

Frost heave is known to be strongly dependant on the confining stress, e.g. Penner & Ueda (1977). The confining stresses around a buried pipeline will generally increase from near zero at the soil surface nearly linearly with increasing depth. This stress state and that superimposed by the frost action must be properly accounted for in any model, whether physical or numerical, of frost heave of buried pipelines. Centrifuge modelling provides such an account.

There are many different theories to describe frost heave mechanics. Yang (1996) provides an overview of 4 of these theories, namely capillary, secondary heaving, segregation potential and segregation freezing. The segregation potential (SP) theory of Konrad and Morgenstern (1980) is widely used in Canada, although other more recent developments such as Ladanyi and Shen (1993) and Selvaduri and Shinde (1993) have been proposed.

Although the theories are different, there is general consensus on the intrinsic and extrinsic factors that affect development of heave, Yang (1996). These factors include grain size, void ratio, temperature effects, confining stress and permeability. All of these factors can be accommodated in a centrifuge model test.

## 2.2 Scaling Considerations

The diffusion of pore water pressures and heat are important processes in frost heave problems. Palmer et al (1985) predicted that centrifuge modelling is able to simulate these two diffusion processes correctly. Savidou (1988) proved this prediction for heat transfer involving only conduction and free convection. Frost heave involves more complex heat transfer including phase transformation, but Chen et al (2000) has shown that centrifuge modelling is applicable even for this more complex process.

Miller (1978) presents a mathematical description of his Rigidice frost heave theoretical model, and Miller (1990) conducted a scaling analysis of the governing differential equations of this model. This analysis and the distinct role of gravitational body force in the heaving process led Miller to conclude that scale modelling of frost heave would best be conducted as a body force analog and that a small-scale frost heave test conducted in a centrifuge would be appropriate for this purpose. On the basis of Miller's earlier unpublished discussions on model laws for soil freezing, Black (1985) also presented a set of scaling relationships for frost heave centrifuge modeling and demonstrated that great time savings would be obtained over a full-scale experiment, Ketcham & Black (1995).

The resulting scaling laws relevant to cold regions modelling are given in Table 1. The scaling laws for centrifuge modelling of frost heave have been confirmed by Chen et al (1993a), Ketcham et al (1997) and Yang (1996).

Table 1: Centrifuge Scaling Laws (after Ketcham et al 1997 and Smith 1995)

Physical Quantity	Prototype	Model
Displacement	1	1/N
Area	1	1/N <sup>2</sup>
Volume	1	1/N <sup>3</sup>
Acceleration	1	N
Stress	1	1
Force	1	1/N <sup>2</sup>
Strain	1	1
Temperature	1	1
Time (Diffusion)	1	1/N <sup>2</sup>
Time (Inertial events)	1	1/N
Time (Viscous flow)	1	1
Interstitial water velocity	1	N
Moisture flux	1	N
Heat flux	1	N

### 2.3 Limitations

There are obvious potential scaling conflicts from this table, such as the simultaneous modelling of time effects relating to diffusion, inertia and viscous flow. However, such potential conflicts are common in reduced scale physical modelling in engineering. Consider modelling of hydraulic systems where the processes are controlled by such dimensionless groups as Reynolds number, Froude number, Mach number and Weber number. The only way to satisfy all of these conditions simultaneously would be to use a full-scale model, which is generally impractical or too expensive. Instead the modeler chooses only to reproduce those processes in the reduced scale model that are pertinent to their problem, while remaining aware of the possible influence of those processes that were not scaled. The same approach is valid for centrifuge modelling, for example, in frost heave modelling inertial events are unlikely to be of any significance and would not be scaled.

Specific frost heave related considerations include the grain size of ice generated in a centrifuge, frozen fringe thickness and the effects of creep, which are discussed by Smith (1995).

Fine and medium grained soil used in a centrifuge test generally has the same grading as that found in the prototype. Coarser grained soils may give rise to particle size effects. If there are insufficient soil particles in the physical model, then the model behaviour will be significantly constrained by the discrete particulate nature of the model, rather than having the appearance of continuum behaviour. Continuum like behaviour is generally observed when there are more than about 25 soil particles in contact with a structure. For a 25mm diameter model pipe, therefore, the mean soil particle size should not be more than 1mm, that of a coarse sand particle. Palmer et al (2003) show the influence of particle size in pipe uplift model tests in granular soils on the distance to mobilise uplift resistance. This influence is not considered to be significant for

centrifuge tests of frost heave of pipelines buried in fine-grained soils such as silt or clayey silt with grain sizes of 0.001 to 0.1mm. This particle size influence on any underlaying or overlaying sand layers or beds in a model should not be significant provided there is no significant shear straining, e.g. rupture band formation, through these areas.

There is evidence from sea ice grown in a centrifuge under an accelerated gravitational field that the ice grains formed are proportionally smaller than those grown in earth's gravity, Barrette et al (1999). Considering the soil grain size ratio is then 1:1 but the ice grain size is not, Smith was concerned that the frozen soil will then not be identical to the prototype and therefore may respond differently. This would affect for example the permeability for water flow through the frozen fringe. Ketcham *et al.* (1997) also raised concern of the scaled down geometry of the ice lens formations. Yang (1996) showed that ice lens seem to be scaled generally in terms of spatial frequency and size.

Ketcham et al. (1997) and Smith (1995) question the time scaling of creep. If creep is a function of temperature and stress which are at a 1:1 scale between model and prototype then the time scale of creep will also be 1:1, which is in conflict with heat diffusion and pore water diffusion that obey a time scale of  $1/N^2$ . The creep of frozen soil in response to frost heave loading and its conflicting time scale may affect model/prototype similitude. Creep will result in stress relaxation that will become more apparent, the longer the duration of the test. There may be evidence of such relaxation in the constrained footing tests conducted by Ketcham et al (1997).

Ketcham et al (1997) also indicated that the period between initiation of freezing and initiation of uplift loads does not scale to  $1/N^2$  as the frost heave process does. This observation is not considered to be correct. Their tests were conducted on a 19 to 29mm thick layer of saturated silt preconsolidated to 35kPa vertical stress. The freezing process was initiated prior to the soil sample being subjected to an increase in centrifuge speed to test acceleration level of 67, 80 or 100g. This self-weight increase causes immediate settlement and primary consolidation movements, which would persist for a period of about half an hour. Any vertical settlement will separate the soil from the suspended constrained footing. There will then be an inevitable delay until the frost heave has compensated for this settlement and forces are measured on the footing. This delay will vary partly because the overconsolidation ratio varied between the 3 tests. In more recent C-CORE frost heave tests, emphasis has been placed on ensuring that primary consolidation is effectively complete before commencing soil freezing. In these tests there has been no evidence of a significant period between the initiation of freezing and the initiation of frost heave.

Despite the limitations stated above, centrifuge modellers to date believe that the tests performed to date support the use of a centrifuge to model the frost heave process.

## 2.4 Validation

The challenge to all modellers of systems is to demonstrate that their model results are sufficiently valid to permit the model to be used in predicting system response over a wider parametric range. Comparing the model results to actual system measurements best does this

validation. However, for geotechnical systems the actual system conditions may be poorly defined and the response of the system to infrequent design events unknown. Alternative means of validation are then required. This may include the comparison of model results with those developed from a second model based on a different set of assumptions. For example, the results of a physical model may be compared to those from a numerical model.

If earthquake engineering is considered, there are data of site response to earthquakes and liquefaction, but very few of these data are associated with well-defined site conditions that existed prior to the earthquake. Centrifuge modelling, developed over the last 20 years, has however gained increased acceptance to provide much needed system response modelling. A report by the Advisory Committee for the National Earthquake Hazard Reduction Program in the USA emphasized the importance of focused research, including centrifuge modelling, to provide results of immediate use to earthquake hazard mitigation. Industry has also accepted centrifuge modelling for this application. The Port of Los Angeles has expanded its facilities through the Pier 400 project. The Port authority required extensive centrifuge model tests to verify and improve the seismic designs of the breakwaters and harbour front structures. Similar centrifuge model tests have been conducted in Cambridge, England of the performance of proposed remediation schemes for the nuclear submarine pens at Devonport in a low-risk earthquake zone. Performance data for such an important facility in a low-risk zone cannot be attained by any other means in a short time frame.

A centrifuge model test is an independent physical event. It may not provide an ideal simulation of the prototype conditions under consideration. However, the engineering insight provided by such tests can be extremely valuable. A centrifuge model test may be viewed as the response of 'the site next door' where conditions are not exactly the same as those of most interest, but are sufficiently close to be of significant interest.

For frost heave of arctic pipelines, there are many coupled processes controlling the system response, such as geothermal conditions, hydrogeological conditions, soil stress-strain behaviour, heat transfer, and pore water migration. The only program of centrifuge modelling of buried pipelines subject to frost heave was initiated by C-CORE 3 years ago. Efforts have been made to simulate the full-scale pipeline frost heave tests conducted at the Calgary test facility, Section 3.1. These simulations have well reproduced the frost heave and heave rates observed from the full-scale tests. There are no publicly available comparisons between numerical models analyses and centrifuge model test data.

An alternative method to validate centrifuge model test data is to conduct 'modelling of models' tests. A 1m diameter pipeline buried at 2m depth could be modeled at 1/10<sup>th</sup> scale using a 0.1m diameter pipe and 0.2m burial or at 1/20<sup>th</sup> scale using a 0.05m diameter pipe and 0.1m burial. If the scaled responses of these two model tests are similar, then confidence is increased that these physical simulations are representative. (Differences in behaviour between the two scales assists in separating the effects of different processes.) Careful consideration is still required however to extrapolate the reduced scale results to a full scale situation. Modelling of models over a wide range of model scales has shown that factors such as frost heave, frost penetration and heave rate do appear to scale correctly in a centrifuge model test, as described in Section 3.

### 3 CENTRIFUGE MODEL TESTS ON FROZEN SOIL

The first centrifuge model tests using frozen soil were conducted in Russia, Pokrovsky & Fyodorov (1969). The University of Bochum, Germany developed this work through model tests including partly frozen artificial sand islands as possible foundations for exploration platforms in arctic regions, Jessberger et al (1983). None of these early tests examined the phase transformation between frozen and unfrozen soil.

Cambridge University conducted the first centrifuge model tests of thaw settlement and frost heave in the early 1990s. Colin Smith, under the supervision of Professor Andrew Schofield, studied the thaw settlement of pipelines using centrifuge model tests for his doctorate, Smith (1991). X Chen, a visiting professor from Tsinghua University, PRC joined Smith in 1992 to initiate centrifuge model tests of frost heave.

Chen et al (1993a) conducted one-dimensional short column frost heave tests of top down freezing using a small-refrigerated desktop centrifuge. Their tests at both 1/100<sup>th</sup> and 1/200<sup>th</sup> scale measured temperatures and surface displacements of the column, Figure 1. The tests clearly showed that the magnitude and rate of frost heave obeyed the expected scaling laws. The success of such modelling of models tests gave confidence to the use of centrifuge testing to examine frost heave issues.

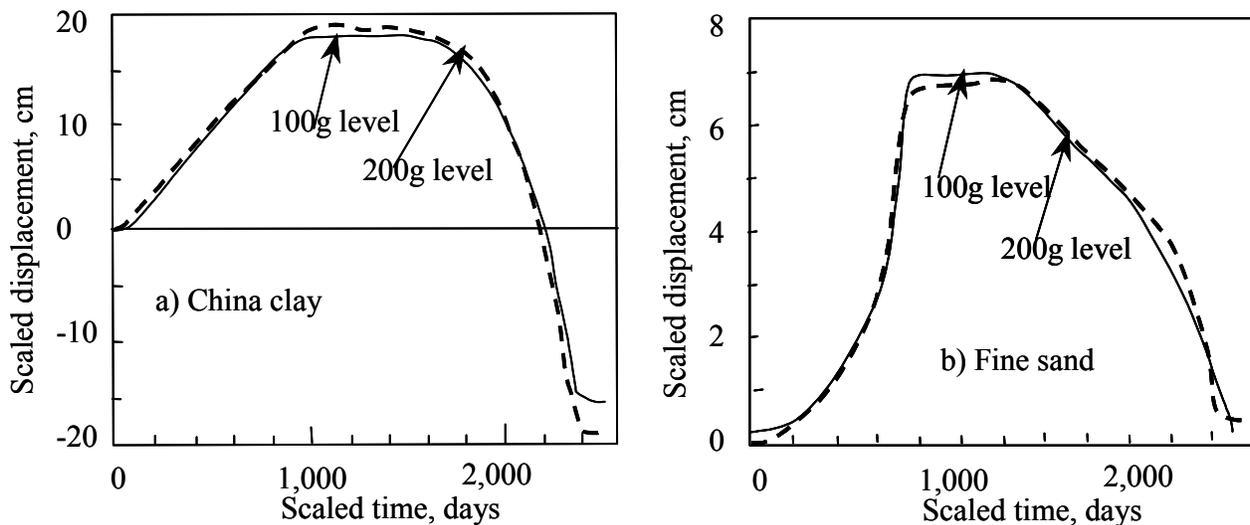


Figure 1: Modelling of models at 100 and 200g, after Chen et al (1993a)

Chen et al (1993b) performed larger size model tests in the 4m-radius Cambridge beam centrifuge of frost heave of buried pipelines. A rigid pipeline section was buried in a vertically partitioned testbed of silt and sand, similar in appearance to one of the full scale tests conducted at the Caen frost heave testing facility, Dallimore and Crawford (1985). Their 1g tests were used to develop the necessary modelling and freezing techniques. The soil model was contained within a passive thermally insulated chamber. Cold gas from a vortex tube was passed through

the model pipe at a temperature of about  $-8$  deg C. Only two tests were conducted in the centrifuge at 45g. The effects of continuous pipe freezing and a freeze-thaw cycle on the resulting frost heave were compared. Chen et al (1994) published the results of these first frost heave tests on buried pipeline. There were no modelling of models tests, and no comparison of results to numerical predictions or full-scale measurements. No further frost heave centrifuge model tests of buried pipelines are known of until Phillips et al (2001).

Following Professor Chen's return to China, he commissioned the centrifuge at Tsinghua University and has continued his frost heave research, Chen et al (1999). Chen et al (2000) considered the effects of freeze thaw cycles on essentially one-dimensional frost heave tests. Modelling of models tests over a narrow range of  $1/40^{\text{th}}$  and  $1/30^{\text{th}}$  scale confirmed the scaling of heat transfer from the ground surface to a homologous point at 6m depth in silty clay. Chen et al (2002) conducted further tests at 40g on silty clay subject to frost heave and thaw settlement. They showed good repeatability of results, such as freeze and thaw fringe, free frost heave and thaw settlement and soil displacement under different loads.

The US Army Cold Regions Research and Engineering Laboratory (CRREL) has considered the application of centrifuge modelling of frost heave since 1985, Scott and Ting (1985) and Ketcham (1990). The US Army Corp of Engineering have developed a large geotechnical beam centrifuge centre, which anticipated the needs for such cold regions research, Ketcham (1991). Ketcham & Black (1995) made some initial small-scale frost heave experimental observations using a desktop centrifuge. These column experiments were very similar to those conducted by Chen et al (1993a), but did not include any inflight measurements or modelling of model tests.

Ketcham et al (1997) developed the application to measure the frost heave loading from top down freezing on a constrained surface footing using centrifuge modeling at scales of  $1/67^{\text{th}}$ ,  $1/80^{\text{th}}$  and  $1/100^{\text{th}}$  in a 0.5m diameter centrifuge. Their 3 scaled models of a 1.27m diameter footing on a 2m deep saturated silt layer were consistent with a narrow range of footing penetration depths, free field frost heave and reasonable agreement in the temporal variation of uplift force, Figure 2. These results indicated that the expected scale factors are correct and centrifuge modelling appropriate for the study of frost heave loading on foundation members. Similarity issues they recognized that may limit the applicability of the technique included stress relaxation, the scaling of ice lens and the delay between initiation of freezing and subsequent uplift force development. These issues are discussed in Section 2.3. The latter issue is misleading as no time was left to allow consolidation of the samples prior to the initiation of freezing.

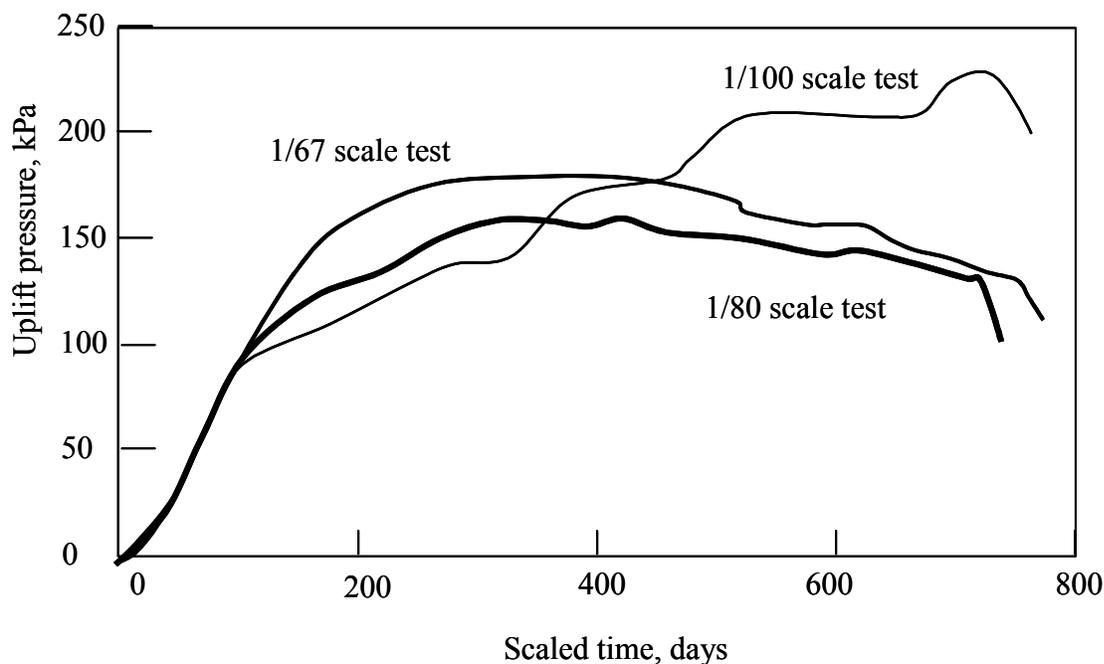


Figure 2: Scaled uplift load response, after Ketcham et al (1997)

Dan Yang, under the supervision of Professor Deborah Goodings at the University of Maryland (UoM) has conducted the most systematic investigation to date of the scaling laws for centrifuge modeling of frost heave in her doctoral thesis, Yang (1996). Six groups of modelling of model tests simulated, using either a pure silt or a naturally occurring silty clay and top down freezing, a one dimensional 3m high soil column at 1/20<sup>th</sup>, 1/30<sup>th</sup> and 1/40<sup>th</sup> scale. For each soil type, two pairs of models were frozen using a step freezing procedure. The first pair had a high water table at 25% of the soil depth, and the second pair with a low water table at 75% of the soil depth. A third pair was tested in silt with a low water table but using a ramped freezing procedure with differing freezing degree-day indices. Thin sections of the frozen samples were examined to obtain ice lens characteristics. The effects of temperature regime, phreatic surface and soil type on soil freezing behaviour were assessed.

The results were compared to short 1g column tests that compared the frost heave dependency on stress level. The modelling of models tests gave strong evidence to support the correctness of the proposed scaling laws: The ultimate heave extrapolated to prototype scale was very close between the 3 scales. Variations within any group were less than 13% from the average value. Frost heave penetration and water content after freezing showed a strong similarity. There was no evidence of adverse scale related effects.

The ice lenses formed at the higher accelerations were clearly smaller in size and closer together than ice lens formed at lower acceleration. Differences were noted in the rate of freezing between ramped and step changes and between soil types. Cumulative freezing degree days were not sufficient to characterize these differences. Results from repeated model tests showed excellent

repeatability with coefficients of variation around 6% for ultimate frost heave, frost penetration and water content.

The centrifuge results were used to calculate bounds on the frost heave monitored at a CRREL field test site. The heave and the frost penetration measured in the centrifuge were similar in magnitude to those measured in similar types of soils, in broadly similar ground surface temperatures and moisture environments. This increases confidence in freezing test data obtained from centrifuge models, Yang (1996).

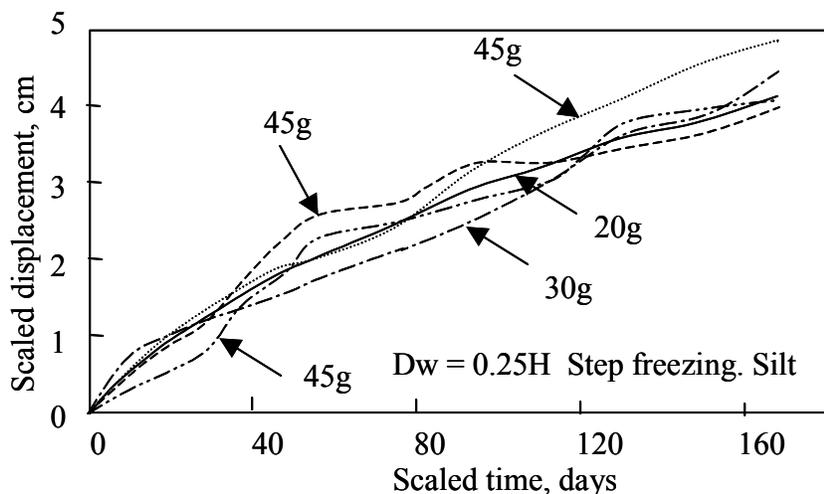


Figure 3: Scaled heave development, after Yang (1996)

The centrifuge measurements in silt were compared to predictions using the CRREL FROST numerical model of Guymon et al (1993). Most input parameters were assessed from laboratory data and accepted data tables. Four parameters were first selected from the CRREL comprehensive documented field site database based on soil type, grain size and heave prediction. This did not provide an acceptable fit to the measurements. These parameters were calibrated using the data from one centrifuge test. Subsequent predictions were excellent compared to the measured heave data. Attempts to calibrate FROST to ultimate heave frost penetration and water content simultaneously were unproductive.

The work of Yang (1996) is summarized in the papers by Yang & Goodings (1998a) and Yang & Goodings (1998b).

UoM has continued working in frost heave looking at boulder jacking through seasonal freezing and thawing, Goodings & Straub (1998) and more recently centrifuge modelling of freezing behaviour of clay, Han & Goodings (2002). They simulated at 35g the freezing behaviour of a 4m deep clay column with a water table 1m below the soil surface. The initial water content had an important role in the development of the freezing response in clay that appeared to be more important than the other mechanical or thermal soil properties. Further developments of this work will be presented in Han & Goodings (forthcoming).

Professors Davies and Harris of the Universities of Dundee and Cardiff respectively have collaborated on a program of centrifuge modelling of permafrost issues related to slope movements and gelifluction, Harris et al (2001), Harris et al (2002), Davies et al (2003) and Harris & Smith (2003).

### 3.1 Frost Heave of Buried Pipelines

Chen et al (1994) published the results of the first two centrifuge model tests of frost heave effects on a buried pipeline, with a similar set up to one of the full scale tests conducted at the Caen frost heave testing facility, as described above. The only other such centrifuge model tests have been conducted at the C-CORE geotechnical centrifuge centre since 2001 as part of an ongoing research program.

These C-CORE tests are summarized in Table 2. A total of 29 two-dimensional pipeline sections have been tested to date, mainly in clayey silt with burial depths ranging from 0.6 to 2 pipe diameters. The maximum test duration in prototype terms was 14 years, or 2 days in a 1/55<sup>th</sup> scale model tested at 55g. The results of the first 3 tests are publicly available as described in Phillips et al (2001), Phillips et al (2002) and Clark & Phillips (2003). The results of the fourth test are proprietary to the Geological Survey of Canada, C-CORE (2001).

Table 2: Summary of C-CORE Centrifuge Model Pipelines Tests of Frost Heave

Test ID	Client	Test Date	Soil Type	g Level	Test Duration	Number Pipes	Burial Depth
Calgary Field Demo 1	None	Mar 01	Clayey silt	30	0.5 yrs	1	0.6D
Calgary Field Demo 2	None	May 01	Clayey silt	30	0.6 yrs	1	1.4D
Calgary Field Demo 3	None	Mar 02	Clayey silt	55	2 yrs	1	0.6D
<b>Proprietary tests follow</b>							
GSC Restrained	G.S.C.	Mar 01	Clayey silt	30	0.4 yrs	1	0.6D
Demonstration	Gas Research Institute	May 02	Clayey silt	42	1.6 yrs	1	0.6D
2002 GRI 1 to 5	Gas Research Institute	Nov 02 - Mar 03	Silt and clayey silt	42 to 55	up to 14 yrs	13	0.75 - 2D
2003 GTI 1 to 5	Gas Research Institute	Aug 03 - Feb 04	Clayey silt	55	up to 13 yrs	10	0.75D
Alaskan Simulation	TransCanada	Jul 03	Layered	55	6.3yr	1	0.82D

The other more recent tests for industry are proprietary to third parties. The objective of the test program for Gas Technology Institute (GTI) was to further evaluate centrifuge technology for use as a tool in predicting the effects of frost heave of chilled buried pipelines and to investigate pipeline behaviour under a range of conditions. A range of conditions are being modeled, including :

- Soil type
- Pipe burial depth
- Pipe Temperature
- Seasonal variations in temperature boundary conditions
- Supply of ground-water to the freezing front

Key issues that were identified in designing the test series included the response of a range of frost susceptible soil types, from a fine grained silty clay to coarse grained silt. The effect of pipe burial depth was also considered important, as it is a well known phenomena that increased pressure on the freezing front reduces the rate of frost heave (Carlson 1982, Konrad & Morgenstern 1980). Increases in burial depth may be the most cost effective and flexible method of limiting frost heave to acceptable levels. Another potential measure for reducing frost heave may be to vary the gas temperature to run periodically at above freezing temperatures. In this way, thaw settlement during warm periods could offset frost heave. Initial test results, backed up with frost heave theory, suggest that these methods could be appropriate and provide cost effective mitigation strategies for maintaining pipe movement within acceptable boundaries at critical points along the pipeline.

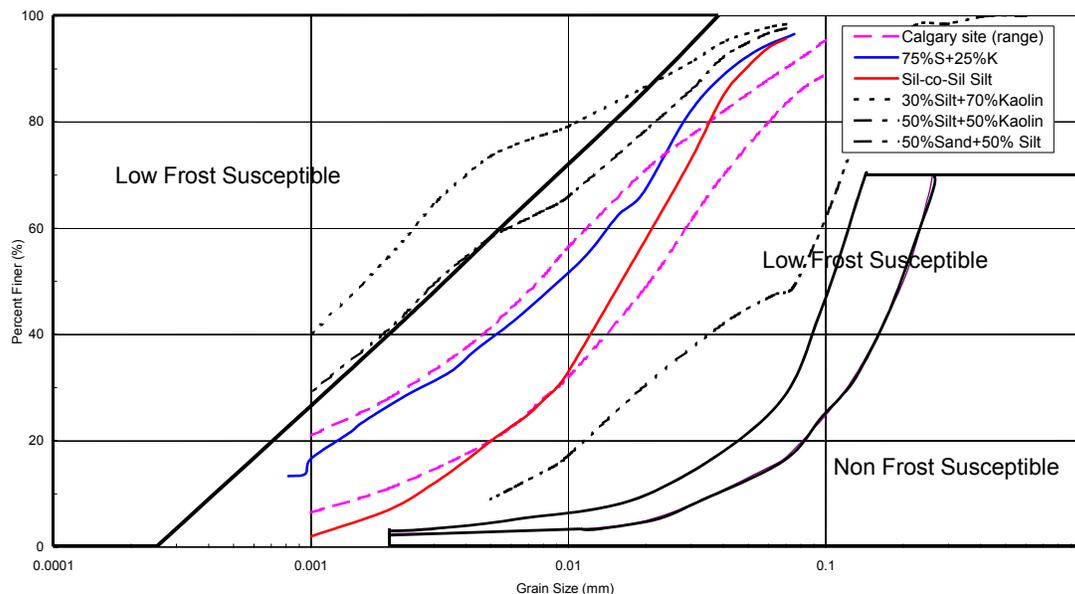


Figure 4: Range of particle size distribution for soils to be used in centrifuge testing

Advances were made in the test set-up to allow multiple pipes to be tested simultaneously within the same package, and a system developed to allow independent temperature control of each pipe during the centrifuge flight. Tests have been performed for a number of soil types and burial depths, and have included the effect of seasonal temperature variation. Figure 4 shows the range of soil gradings that have been tested to date, compared to the range normally considered for frost susceptible soils. The range of soil particle size is prepared by mixing various proportions of kaolin clay and sil-co-sil silt, both materials being easily available to well defined quality standards. No attempt is therefore made to defining the role of mineralogy in frost heave. Burial depths tested are between 0.75 and 2.0 times the pipe diameter. The pipes are generally cooled to  $-10^{\circ}\text{C}$  as a base case, although the effect of warmer temperatures and/or seasonal operation at above-zero temperatures has also been integrated into the program, Morgan et al (2004). The test results are not discussed in this review.

Findings from the first four tests and comparisons with large-scale field tests follow. The first three centrifuge tests provided a comparison with full-scale measurements made at the Calgary test site as presented by Slusarchuk et al (1978). The responses from two of the eventual 6 test sections were simulated, namely the control section and the deep burial section as shown in Figure 5. The fourth centrifuge test simulation for GSC simulated a third section where upward movement of the pipe was restrained by a reaction frame.

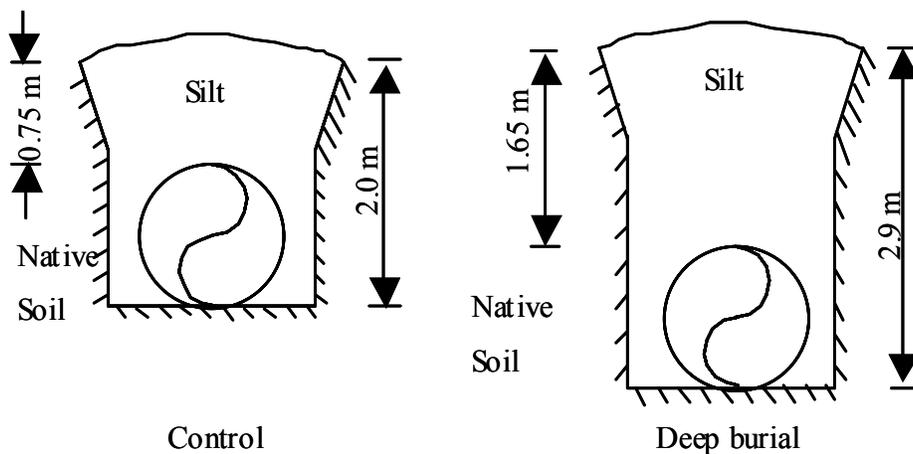


Figure 5: Calgary Ditch Configurations, after Carlson (1982)

Figure 6 shows the range of grain size distributions for the Calgary site and for the samples prepared for centrifuge modeling. The soil used in the modelling study for two tests was a 60%-40% mixture of Sil-Co-Sil silt and Speswhite Fine China kaolin clay. A third test used a 75%-25% mixture. A summary of the properties of the modelling soil and the prototype field soil, preparation procedure and instrumentation are presented in Phillips et al (2002).

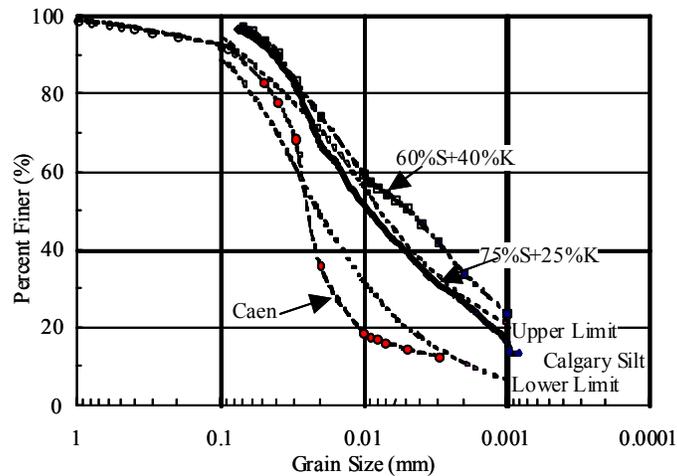


Figure 6: Grain size distributions for Caen, Calgary and model silts

Tests 1 and 3 modelled the control section tested at the Calgary test facility. Test 2 modelled the Calgary deep burial section. A similar thermal response to the prototype conditions was observed. The pipe temperatures are similar between the model and prototype, but the ambient air temperature at the soil surface was an area of model simplification which was modeled as a step change between summer and winter conditions.



Figure 7: Typical post-test pipe cross section Phillips et al (2001)

Figure 7 reveals the typical ice lens formations representative of all three sections. The ice lenses were generated outward from the pipe in a circumferential and radial pattern. The thickness of ice lenses increased with depth below the pipe. Growth of larger ice lenses with increasing

distance from the pipe is consistent with the full-scale condition of a chilled pipeline subject to frost heave and that observed in laboratory tests, Konrad (1994). The radial ice formations shown in Figure 7 are thought to be post-test tension cracks that developed from stress relaxation of the soil when centrifuge operation ceased.

A comparison of the models to the measured field data from the Calgary frost heave test site reveals similar behaviour patterns with respect to heave displacements and time, Figure 8. There is a good comparison between Tests 1 and 3 and the control section, and Test 2 with the deep burial section.

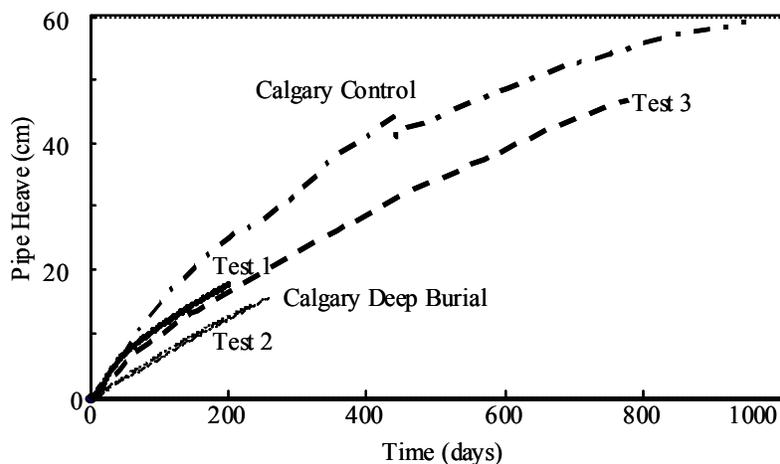


Figure 8: Pipeline heave comparison for Calgary and model tests

Konrad & Morgenstern (1984) show a similarly good comparison between their finite difference segregation potential, SP numerical analysis and the measured performance at the various full-scale test sections. These analyses used the SP value for Calgary silt presented in Figure 9, which also shows the values of SP reported from two different laboratories on samples of kaolin/silt mixes used for centrifuge testing. The SP values for 75%-25% silt-kaolin measured in Laboratory 1 are very similar to those measured at the Calgary test site, but nearly an order of magnitude lower than those measured in the same laboratory for 60%-40% silt-kaolin mixtures. The centrifuge results however do not show a significant sensitivity to these SP readings. SP values of the 75%-25% mixture measured at a second laboratory were significantly lower than those measured at laboratory 1. This suggests that certain difficulties exist in the measurement of SP values in the laboratory, and that the tests are sensitive to preparation procedures and testing techniques.

Figure 10 shows the rate of frost heave plotted against pressure acting on the freezing front for the Calgary test site and for the centrifuge modeling of those sites. This pressure was calculated from the total effective weight of the pipe and a block confined by two lines tangent to the developing frost bulb and rising to the surface at  $60^\circ$  to the horizontal, and the frost bulb base. In addition to the Calgary tests, rate of heave for two test cycles of the 250 mm diameter pipe at Caen, France are shown. The Caen tests have a much lower pressure on the freezing front and

are presented here for comparison only. The tests designated as the second cycle have a much greater heave rate than the first cycle. This is contrary to other small-scale tests.

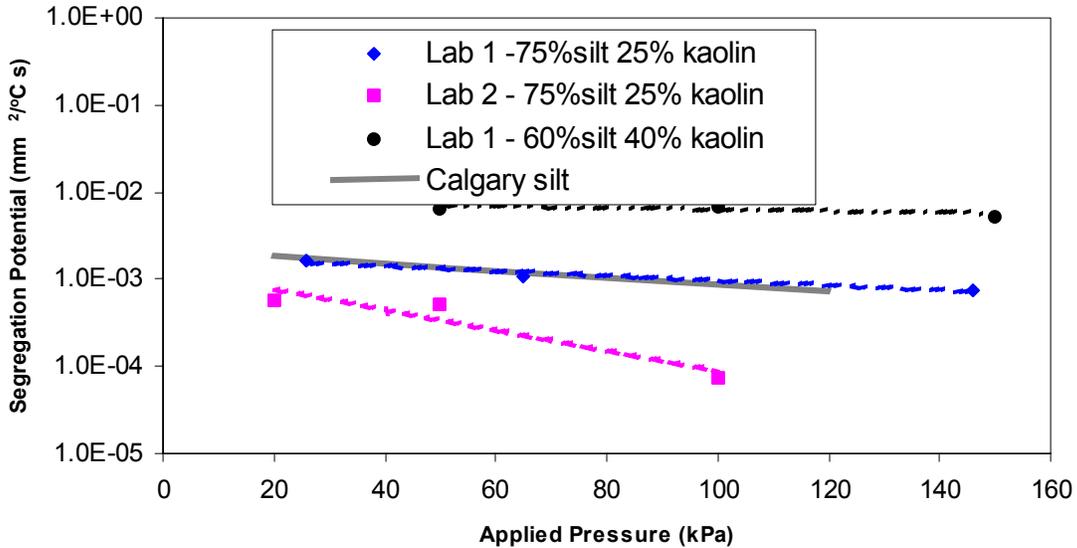


Figure 9: Segregation potential comparison

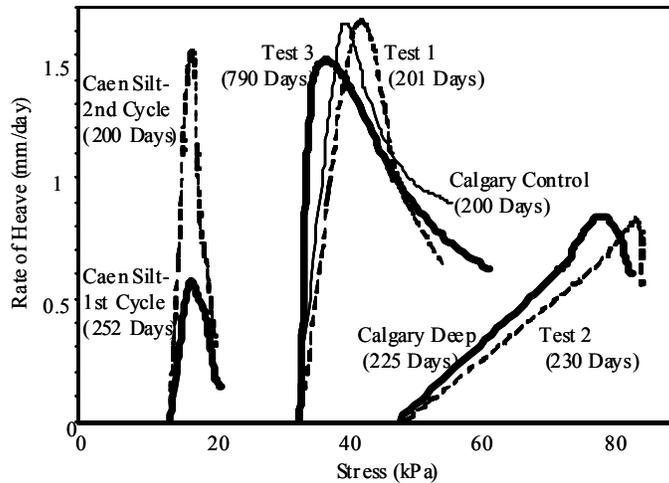


Figure 10: Heave rate with pressure for Caen, Calgary and model tests

The substantial reduction of heave rate due to increased pressure on the freezing front as the frost bulb grows in the full-scale Calgary tests has been replicated by the centrifuge modeling.

A preliminary centrifuge test of the restrained pipe section at the Calgary Frost Heave Test Facility was presented by C-CORE (2001). The model appeared to have yielded the anticipated thermal and heave behaviour. Comparison of pipe heave displacements and restraint loads

between the prototype and the model at full-scale are given in Table 3 for two different time intervals during the test. The thermal and heave response of the model match the prototype. The actual heave measured was very similar for the two pipelines. The magnitude of frost heave forces experienced in the model, at prototype scale, are much greater than the actual prototype. The loads registered at the prototype field-test were under a constant loading restraint and not a zero displacement restraint like the centrifuge model. The constraint on a freezing front has a major influence on the heave force developed. The relative rapidity of the centrifuge test will also have prevented any stress relaxation due to creep.

Table 3: Load and displacement model to prototype comparison

	Freeze time (days)	Pipe heave (cm)	Total load (MN)	Load per unit length (kN/m)
Model	86	5.65	4.4	213
Calgary Prototype	86	4	0.55	45.1
Model	135	7.22	6.0	290.4
Calgary Prototype	135	8	1.81	148.4

#### 4 FUTURE APPLICABILITY TO PIPE FROST HEAVE

Centrifuge modeling linked with simple analytical techniques may be used for efficient design of pipelines for the effects of frost heave.

Emphasis should be placed on demonstrating to the engineering community the repeatability of centrifuge model test data and the validation of these data. This validation should include modelling of models tests of the effects of chilled buried pipes, which have not been conducted to date. Comparisons should also be made to accepted numerical models to further identify the advantage and limitations of both modelling idealizations.

All frost heave pipe centrifuge tests to date have used an effectively rigid pipe section. Centrifuge model tests of flexible pipes have been beneficial in assessing the flexural pipe response to geotechnical loads in other applications, such as differential ground settlement, Hachiya et al (2002). Similar three-dimensional modelling of pipe-soil interaction effects such as across the boundary between frozen and unfrozen soils could be examined. Tests of this nature are planned for later in 2004 at C-CORE.

A semi-empirical design method is emerging, from current centrifuge model tests, that is based on actual heave measurements of pipelines. A range of frost susceptible soils with variable water contents has been tested. A relationship has been developed between rate of heave and pressure on the freezing front. The pressure on the freezing front reflects the initial burial depth and the penetration of the freezing front with time. A predictive semi-empirical model requires a geothermal analysis (several reliable analytical models are available) coupled with a suite of

benchmark design curves from the centrifuge test. The centrifuge model test program can be expanded through a parametric study to include, for example, consideration of different pipe geometries, burial configurations, soil types, and geothermal and hydro geological conditions.

A possible design methodology that establishes risk and reliability that could be refined over the next couple of years, is set out below:

- Establish a suite of frost heave design curves for a range of frost susceptible soils relating heave rate to pressure on the freezing front from centrifuge model tests of generic site conditions. These can be obtained from a limited number of centrifuge tests as described above.
- For each terrain unit along the proposed route, estimate the frequency and length of unfrozen soils.
- Establish engineering design criteria for specified limit states through empirical investigations, analytical studies and numerical modeling.
- Assess the system reliability for each limit state. Establish target safety levels for acceptable or tolerable risk. Based on the reliability targets, define failure consequences and conduct the risk analysis that would ensure the established target safety level is achieved.
- Based on the risk-based approach, establish depth of burial for each section, spread or terrain unit.

For critical areas, analyze predicted frost heave at frozen/unfrozen boundaries and frost susceptible/non frost susceptible boundaries and maximum heave in unfrozen sections in relation to established strain criteria. Critical areas along the pipeline route may include the location of changes in terrain, pipe bends, slope areas or approaches to compressor stations. This analysis may include site specific centrifuge model tests. Such tests can also assist in identifying mitigation activities that may include seasonal cyclic operation. Centrifuge testing may also have a role during the operational phase of the pipeline, as unexpected site conditions and pipe response are revealed. Testing may help to identify the cause of this response and provide insight into remediation or mitigative measures.

The combined approach of using centrifuge modeling, numerical analysis and structural limit state design methods would provide a cost effective method that could address a range of conditions to define the frost heave behaviour of a pipeline.

## **5 DESIGN, ENVIRONMENTAL, SAFETY & SECURITY ISSUES**

The use of centrifuge testing to date has focused on two areas; (1) establishing that centrifuge testing as a valid technology to use for modeling of ground freezing behaviour, and (2) demonstrating that centrifuge testing can be used to model complex boundary and operating conditions that are not easily analysed using existing tools. The results of centrifuge tests to date suggest that it may be suitable for use as a design tool and also to investigate the effects of various operational strategies.

Following the initial demonstration tests, the use of centrifuge testing to investigate the specific issues relating to pipeline design and operation in northern regions has been performed at C-CORE under contract to PRCI and is therefore proprietary. As such, specific details cannot be discussed, although general comments can be made relating to how these test results could be used for pipeline projects.

A number of tests have been performed that provide insight into the behaviour of pipelines as a result of growth of a frost bulb due to transportation of chilled gas. Some of these observations are not included in current analytical models and highlight the benefits of physical testing. Tests suggest, for example, that certain soils can undergo consolidation as pressure is applied due to frost heave. The pressure generated at the freezing front as ice lenses are generated may induce consolidation of the underlying unfrozen soil, offsetting frost heave displacement and resulting in much reduced pipeline movement.

Similarly, varying the gas temperature between above and below freezing temperatures results in a complicated series of frozen and unfrozen annuli, which may cause numerical instability when analysed. At the very least, an understanding of the complex heat transfer conditions at each of the frozen / unfrozen boundaries is difficult to obtain analytically. The results of centrifuge tests that model this behaviour may be the most flexible method of quantifying such effects.

The analysis of other issues with complex boundary effects would also be suitable for modeling in the centrifuge. Examples could include the effects of soil surface temperature, thawing slope stability, river crossings or effects of surface cover.

In addition to providing direct observation of complex behaviour as described above, the results of centrifuge tests can be used to calibrate numerical analysis, allowing capabilities of these tools to be developed and enhanced. By carefully controlling boundary and test operating conditions, direct comparisons with analytical models can be obtained with minimum extrapolation of results.

Evaluation of environmental, safety or security issues may be better achieved using other methods, although specific geotechnical processes such as contaminant transport have been modeled in the centrifuge. The results of centrifuge tests can be used as input into various risk models when considering safety and security issues.

## **6 CONCLUSION**

Over the past three decades, centrifuge modeling has become a widely accepted tool for the prediction of the behavior of soil-structure systems, as it provides a cost effective and quick method to analyse the behavior of geotechnical systems, especially in areas in which full scale testing is difficult or impossible to achieve. Centrifuge modeling, because of this reduced scaling, accelerated time frame for controlled testing and cost effectiveness provides a unique opportunity for use in the prediction of frost heave and the design development for arctic pipelines

A centrifuge model test is an independent physical event. It will not provide a perfect simulation of the prototype conditions under consideration. However, the engineering insight provided by such tests can be extremely valuable, especially with an appreciation of the modeling issues, which could distort the results. For frost heave of arctic pipelines, there are many coupled factors controlling the system response, such as geothermal conditions, hydrogeological conditions, confining stress variation, soil stress-strain behaviour, heat transfer, and pore water migration. Most of these factors are reasonably modelled in a centrifuge test.

There are frost heave related modelling issues to be considered, including the grain size of ice generated in a centrifuge, the frozen fringe thickness and the effects of creep. These considerations need to be put into perspective through further research.

A method to validate centrifuge model test data is to conduct ‘modelling of models’ tests. If the scaled responses of the two model tests at different scales are similar, then confidence is increased that these physical simulations are representative (Differences in behaviour between the two scales assist in separating the effects of different processes). Modelling of models of one dimensional frost heave over a wide range of model scales has shown that factors such as frost heave, frost penetration and heave rate do appear to scale correctly in a centrifuge model test. These models also showed good repeatability of results, such as freeze and thaw fringe, free frost heave and thaw settlement and soil displacement under different loads.

This modelling of models technique should be used to validate pipe response to frost heave, coupled with tests to demonstrate repeatability of results.

Comparisons made between centrifuge model results and those from full-scale pipeline frost heave testing undertaken at the Calgary test site, Clark & Phillips (2003), revealed similar behaviour patterns with respect to heave displacements and time. A similar thermal response to the prototype conditions was also observed. The substantial reduction of heave rate due to increased pressure on the freezing front as the frost bulb grows was replicated. The circumferential ice lenses generated outward from the model pipe increased in thickness with increasing distance from the pipe, which is consistent with the full-scale condition of a chilled pipeline subject to frost heave and that observed in laboratory tests.

There are currently no publicly available suitable numerical model results and no operating chilled pipelines in existence against which to extend this comparison. The verification of the results of centrifuge modeling has exactly the same constraints as analytical, empirical or semi-empirical methods. That is it requires full-scale behavior to which it can be compared.

A semi-empirical design method is emerging, from current centrifuge model tests, which includes a relationship between rate of heave and pressure on the freezing front. The centrifuge model test program should be expanded through a parametric study to include, for example, considerations of different pipe geometries, burial configurations, soil types, and geothermal and hydro geological conditions. The program can also evaluate heave mitigation strategies and pipe soil interaction through, for example, discontinuous permafrost.

## 7 GLOSSARY OF TERMS RELATING TO CENTRIFUGE TESTING

Some of the terminology used in this report relating to centrifuge testing has been included within this glossary to aid readers who may be unfamiliar with this technology:

**Geotechnical Centrifuge** – Equipment designed for testing scale models of geotechnical processes under enhanced inertial acceleration field. Operated by spinning the test package about an axis such that additional ‘gravitational’ acceleration acts radially outwards.

**Test Package** – The module containing soil, structure and instrumentation that undergoes testing in the centrifuge.

**Centrifugal Acceleration** – acceleration applied to the test package as it spins at the end of the centrifuge arm, as a function of the radius to the package and rotational velocity during operation.

**Centrifuge Flight** – The process of spinning up, testing and spinning down the centrifuge equipment.

**Scaling Laws** – laws that describe the scale effects of model testing in the centrifuge. Developed using a combination of dimensional analysis, theory and empirical physical relationships.

**Prototype Scale** – Consideration at full-scale the behaviour of the structure or process being modeled.

**Model Scale** - Properties describing the model behaviour without scale factors being applied.

**Modeling of Models** – the testing of models over a range of scales to establish the scaling laws relating to the process being modeled.

**Stress Similitude** – The application of identical soil stress states in prototype and homologous points within the model.

**In-flight Consolidation** – the process of establishing equilibrium of the soil package in the centrifuge prior to performing the test. The application of enhanced gravity and associated stress fields to a fine-grained saturated soil usually results in consolidation, which must be substantially complete prior to starting the testing process.

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## APPENDIX A – REVIEW OF CENTRIFUGE MODELLING OF FROST HEAVE

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### 1. Introduction

Geotechnical centrifuge modeling is a tool that has developed over the past seventy years for the investigation of the behavior of geotechnical structures. Although first proposed by Edouard Phillips in 1869, the first centrifuge tests were carried out in the former USSR by Pokrovskii & Fiodorov [1] in 1931. Over the past three decades, centrifuge modeling has become a widely accepted tool for the prediction of the behavior of soil-structure systems, as it provides a relatively cheap and quick method to analyse the behavior of geotechnical systems.

### 2. Principles

Small scale modeling of geotechnical processes is highly desirable, as it provides a cheaper, quicker and more controllable route to an understanding of geotechnical system behavior than full-scale testing. In order, however, for this small scale modeling to be worthwhile, the scaling of behavior from large to small scales needs to be understood.

Small-scale modeling in general interprets the behavior of a small, highly instrumented model to imply the behavior of a large prototype system under homologous circumstances.

As soil is a highly non-linear material, whose strength and stiffness are functions of stress level, it is almost impossible to scale the behavior of a model to that of the prototype unless the stress states at homologous points in the model and prototype are identical. As in a geotechnical structure such as a dam, all (or almost all) of the stresses acting on any soil element within the structure come from the self-weight of other soil or water elements, it is impossible at 1-g to replicate the stress field within the prototype in the model structure. If, however, a 1:N scale model constructed of the same materials as the prototype is tested at  $Ng$  within the enhanced gravity field of a geotechnical centrifuge it can be shown that the stresses and strains within the model are identical to those at homologous points within the prototype.

### 3. Scaling Laws

We have seen in the previous section that the stresses and strains in a 1:N scale model tested at  $Ng$  are the same in model and prototype structures. However, in order to extend the interpretation of centrifuge test data, scaling laws need to be derived for other parameters. Many of these scaling laws can be derived either from dimensional analysis or by evaluation of known relationships between parameters for which scaling laws have been derived. For example:

Suppose we want to calculate the scaling law for force for a 1:N scale model tested at Ng.

a) By dimensional analysis:

Force has dimensions of  $MLT^{-2}$

Length has dimensions of L, and scales as  $1/N$

Acceleration has dimensions of  $LT^{-2}$  and scales as N

Density has dimensions of  $ML^{-3}$  and scales as 1

Thus from length and acceleration we can imply that time scales as  $1/N$

From length and density we can imply that mass scales as  $1/N^3$

Therefore, force scales as  $1/N^2$

b) From a known relationship

Weight = Density x Volume x Gravity

$1/N^2 = 1 \times 1/N^3 \times N$

By following this example, we can determine scaling laws for a wide variety of quantities, as summarized in Table 1. These scaling laws have been divided into those with scales chosen by the modeler, those with scales forced on us by our decision to use the same materials in the model as are present in the prototype and those which can be derived from combinations of other scaling laws.

Table 1: Scaling laws in centrifuge modeling (after Schofield [2])

	Quantity	Dimensions	Model / Prototype
Chosen scales	Length	L	$1/N$
	Acceleration	$LT^{-2}$	N
	Stress	$ML^{-1}T^{-2}$	1
	Strain	Dimensionless	1
Material scales	Density	$ML^{-3}$	1
	Permeability	$LT^{-1}$	1
	Particle size	L	1
Derived scales	Dynamic Velocity	$LT^{-1}$	1
	Seepage Velocity	$LT^{-1}$	N
	Dynamic Time	T	$1/N$
	Seepage Time	T	$1/N^2$
	Force	$MLT^{-2}$	$1/N^2$

It can be seen from the above table that inconsistencies occur between the scaling laws for quantities which are dimensionally similar such as the times taken for dynamic and seepage events to occur. These inconsistencies occur owing to the non-scaling of particle size and

permeability from prototype to model. This can have important implications for models in which inertial loading is significant, as will be discussed in Section 4.4.

## 4. Similarity

In order for the prototype behavior to be properly scaled in the model, the features that must be achieved in the centrifuge tests are:

- a) Geometric similarity
- b) Water flow similarity
- c) Thermal similarity
- d) Dynamic similarity
- e) Identical constitutive behavior

These will be dealt with in turn for a general centrifuge model.

### 4.1 *Geometric similarity*

Geometric similarity between model and prototype is always assumed in centrifuge modeling at the macro-scale. This implies that all components of the model, (e.g. soil depth and extent and foundation sizes), are scaled down by a factor  $N$  from prototype to model, as shown in Table 1. This similarity, however, does not exist at the micro-scale, as particle sizes are not usually scaled down from prototype to model. Scaling down of particles would significantly alter the constitutive behavior of the soil and is hence undesirable. Keeping identical particle sizes in model and prototype can, however, cause problems when either the size of items interacting with the soil, (such as pipes), becomes close to the size of soil grains, or when shear bands whose thicknesses are a function of particle size are present.

Both of these length scale conflicts have been quantified in the literature. Authors such as Ovesen [3] have studied the effect of the ratio of particle size to component size in boundary value problems such as bearing capacity and penetration resistance. In general it has been recommended that the ratio of component size to particle size should not fall below a value of 30 in order to avoid excessive errors.

Palmer *et al.* [4] carried out both full-scale 1-g tests and centrifuge tests looking at the uplift resistance of buried pipelines in order to quantify scale effects on shear band formation. They found that the displacement required to mobilize the full uplift resistance in a sand with  $D_{50}$  of 0.27 mm was approximately 2.5mm both at 1-g and at 10-g (unscaled). From this they surmised that localized shear zones are not properly scaled in the centrifuge, owing to non-scaling of particle size, and that this can have a significant impact on mobilization distances. While macro-scale constitutive relationships scale properly in the centrifuge, any localization of strains into shear bands will be governed by the scaling of particle size, rather than global dimensions, and hence may not scale properly in the centrifuge.

#### 4.2 Water Flow Similarity

In order for similarity of behavior to be observed between model and prototype, the correct pore-fluid flow regime must exist within the model. This implies that the fluid pressure at homologous points in space and time must be identical.

Fluid flow in soils is governed by d'Arcy's Law:

$$v = -k\nabla h$$

In which  $v$  is the fluid velocity,  $k$  is the permeability of the soil and  $h$  is the pore-pressure head. It can be shown that in a geometrically similar model of 1:N scale at  $Ng$ , stresses and hence pore-pressures at homologous points are identical and thus, as the distances in the model are  $N$  times smaller than in the prototype, the gradients of pore-pressure head scale as  $N$ . Thus, as permeability is identical in model and prototype, flow velocity scales as  $N$ .

The time taken for the water to flow a certain distance in the model thus scales as  $1/N^2$ , as the velocity is  $N$  times higher in the model, and the distance traveled is  $N$  times lower.

Consolidation time also scales as  $1/N^2$ , as it is a seepage driven process. This can be shown by considering Terzaghi's 1-D consolidation equation:

$$\frac{\partial u}{\partial t} = \frac{k}{m_v \gamma_w} \frac{\partial^2 u}{\partial z^2}$$

where  $k$  is permeability,  $u$  is excess pore pressure,  $m_v$  is the coefficient of volume compressibility and  $\gamma_w$  is the unit weight of water. It can be seen that in the centrifuge model,  $k$ ,  $m_v$  and  $\gamma_w$  are identical as they are material properties. It can also be seen that the excess pore-pressures must be the same in model and prototype for stress similarity to exist. As the dimension  $z$  is  $N$  times smaller in the model than in the prototype,  $\partial^2 u / \partial z^2$  must be  $N^2$  times larger in the model. The rate of change of pore pressure must hence also be  $N^2$  times larger, so the time for consolidation to occur scales as  $1/N^2$ .

This scaling law holds provided that the soil is identical (not scaled) on a micro-scale between model and prototype, and hence that permeability is identical between model and prototype.

The scaling law on time of  $1/N^2$  is one of the major advantages of centrifuge modeling over 1-g full-scale testing, as it means that the long-term behavior of geotechnical systems can be investigated in a reasonable timescale. For example, a model clay embankment tested at 100-g for 24 hours would simulate 30 years of prototype time.

The validity of these scaling laws for fluid flow have been demonstrated under certain sets of circumstances by Arulanandan *et al.* [5] and Celorie *et al.* [6].

#### 4.3 Thermal Similarity

Thermal similarity implies that temperatures at homologous points in the model and prototype at equivalent times are identical. It is obviously simple to maintain the thermal boundary conditions of the model to be identical to those of the desired prototype, however the heat flow equations must be studied in order to check that there is no inconsistency between the time scaling laws for thermal and other processes. Heat conduction can be described by the equation:

$$C \frac{\partial \theta}{\partial t} = K \nabla^2 \theta$$

in which C is specific heat capacity, K is the thermal conductivity and  $\theta$  is the temperature.

For a geometrically similar model comprising the same soil as the prototype, C and K are identical in model and prototype. As the temperatures are identical at homologous points but the length scales as  $1/N$ , the temperature gradients scale as  $N$  and  $\nabla^2 \theta$  scales as  $N^2$ . The rate of change of temperature thus scales as  $N^2$ , implying a time scale factor of  $1/N^2$ . It can be seen from the previous section that this time scale factor is identical to that for seepage processes and hence no inconsistency occurs in the simultaneous modeling of thermal and fluid flow processes. It can also be shown that heat flux (energy flow per unit area) will be  $N$  times greater in the model than in the prototype.

Thermal processes coupled with fluid flow in centrifuge models have been investigated by Savvidou [7 & 8] and by Booker & Savvidou [9].

#### 4.4 Dynamic Similarity

Dynamic similarity implies that the scaling of forces is identical, regardless of the origin of these forces. Ketcham and Black [10] derived the following force scaling laws:

- 1) Self-weight force scales as  $1/N^2$
- 2) Seepage force scales as  $1/N^2$
- 3) Inertia force scales as 1 (if time is scaled as  $1/N^2$ )
- 4) Viscous force scales as 1 (if time is scaled as  $1/N^2$ )

Thus it can be seen that dynamic similarity is only achieved with a time scaling factor of  $1/N^2$  if inertial and viscous forces are not important in the situation modeled. This implies that accelerations and fluid velocities within the model should be small.

If accelerations within the model are not small, as is the case in the modeling of earthquake effects, the inertial force conflict can be overcome by using a pore-fluid such as silicone oil of viscosity  $N$  times higher than that of water, (as in Haigh *et al.* [11]). This drops the permeability of the soil to the pore fluid by a factor  $N$  and hence drops seepage velocity. A time scale factor of  $1/N$  can then be used with self-weight, seepage and inertial forces all scaling as  $1/N^2$ . The disadvantages of this approach are that consolidation now takes  $N$  times longer than when using water as a pore-fluid, lessening one of the advantages of centrifuge modeling, and that heat transfer processes are not slowed down and hence are incorrectly scaled.

#### 4.5 Identical Constitutive Behavior

Identical constitutive behavior between model and prototype is usually assured by using the same soil in the model as is present in the prototype. This holds provided that there is no dependence of the constitutive behavior on either sample scale or strain rate.

Sample scale is important either where localization of strain occurs forming shear bands whose thickness is a function of particle size, as discussed in Section 4.1 or for brittle materials such as ceramics in which strength varies with the size of sample chosen owing to the presence of cracks within the material.

Rate effects on constitutive behavior include creep, in which strains accumulate over time allowing stress relaxation. This behavior will not necessarily be accelerated by the same factor  $N^2$  as the model time and hence may not be correctly modeled.

### 5. Modeling of Models

If a case arises where the equations governing the model behavior are not well understood, the applicable scaling laws can be derived or checked using the technique of “modeling of models”. This technique involves the testing of two or more models of the same prototype at differing g-levels and then using the relationship between the results of the two tests to determine the applicable scaling laws.

For example, suppose we wished to investigate the bearing capacity of a 10m diameter shallow foundation. This foundation could be modeled either as a 10cm diameter foundation tested at 100g or as a 20cm diameter foundation at 50g.

Once these two tests had been carried out, suppose that model A exhibited a foundation settlement of 1mm under a load of 20N, whereas model B showed a settlement of 2mm with a load of 80N. We know from our initial scaling laws on length that these two model settlements both correspond to 10cm of settlement at prototype scale, and hence both forces must also correspond to the same force at prototype scale. Thus if we assume that our scaling law is a power law:

$$F_{prototype} = F_A \times N_A^x = F_B \times N_B^x \Rightarrow x = \frac{\log\left(\frac{F_A}{F_B}\right)}{\log\left(\frac{N_B}{N_A}\right)}$$

Therefore in our example, the power  $x$  is  $\log(20/80) / \log(50/100) = 2$ . So the force scales as  $1/N^2$ . This technique can also allow us to verify that the scaling we have derived by other means is valid, as the results from two tests of identical prototypes at different scales should be identical within the experimental error when plotted at prototype scale.

## 6. Known Modeling Issues

There are several sources of error implicit in centrifuge modeling whose impact should be quantified when carrying out a centrifuge modeling program. These include:

- g-field curvature: As the g-field in a centrifuge is radial, the equipotentials at the model are not straight but curved, resulting in distortion of the stress field. This error is small when the model width is small relative to the centrifuge radius.
- Variation of g with radius: As centripetal acceleration is proportional to radius, the g-level in a model becomes progressively greater with depth through a soil layer. This error is small when the model is shallow relative to the centrifuge radius.
- Particle size scaling: As mentioned in Section 4.1, as particle sizes are not scaled down by  $N$  between prototype and model, any model in which shear bands are created may exhibit incorrect scaling of mobilization distances.
- Time scaling laws: If significant inertial or viscous forces are present in the model, the differing time scaling laws of inertial, viscous and seepage forces need to be considered.
- Creep: The scaling law on creep may be inconsistent with other scaling laws in the model.
- Boundary effects: Boundaries should be designed to minimize their effects on the model. They should be stiff enough to maintain  $K_0$  stresses and smooth, in order to minimize their effects on the vertical stress state within the model. Boundaries should also be kept sufficiently far away from regions of interest to minimize their influence on failure mechanisms.

## 7. Frost Heave Theory

When ground surface temperatures or the temperatures of pipes passing through soils fall to below the freezing point of water, they will cause the soil at the interface to begin to freeze. As water expands by 9% on freezing, a certain amount of ground heave would be expected, however, migration of water into the freezing areas causes this problem to be much more severe. In freezing soils, the pore water is in equilibrium with ice crystals forming within the soil pores. As the ice crystals grow they impart a stress on the soil skeleton surrounding the pore. When this stress becomes equal to the total stress acting on the soil at this location, (i.e. effective stress falls to zero) the soil skeleton is fractured and an ice lens is initiated. As the ice lens grows, water is removed from the pores to form ice, reducing the fluid pressure surrounding the lens. This causes further water to be drawn towards the lens due to the pore-pressure gradient set up. If the rate of

freezing of water at the ice lens, (governed by the outflow of heat), is matched by the inflow of water due to the pressure gradient, the ice lens will continue to grow. If the inflow of water is insufficient to match the rate of freezing, water within the soil pores surrounding the ice lens will begin to freeze in what is known as the “frozen fringe”, further reducing the soil permeability. If at any point within this frozen fringe effective stress falls to zero, a new ice lens will be initiated. As water is drawn into these ice lenses from elsewhere in the soil bed, a volumetric expansion takes place, resulting in frost heave. This heave can cause distortions of the ground surface if freezing is progressing downwards from the ground surface, or heaving of pipes if they are causing the soil surrounding them to freeze.

In order to determine how this problem will scale in the centrifuge, we must consider each of the principles of similarity discussed in Section 4. Geometric, thermal and fluid flow similarity can easily be satisfied for the initial soil configuration. Dynamic similarity will also be achieved with a time scale of  $1/N^2$ , as the fluid velocities and solid accelerations within the model are small. The constitutive behavior of the initial unfrozen soil can also be assumed to be identical to that of the prototype, as no significant strain localization has occurred prior to freezing.

As freezing progresses some issues begin to become relevant to the scaling. These issues can be divided into three areas:

1. Ice crystal formation
2. Ice creep & fracture
3. Uplift resistance mobilization

### *9.1 Ice Crystal Formation*

As was mentioned in Section 4.1, two distinct scaling laws for length exist within the model, macro-scale lengths and displacements being scaled by  $1/N$ , whereas micro-scale lengths, such as particle sizes, are unscaled. This may cause problems as ice crystals grow within the soil, as crystals may exist both as macro-scale ice lenses and at micro-scale within pores. It is also uncertain what the scaling law is for ice-crystal growth under increased gravity.

Experiments conducted by Langhorne & Robinson [12] and Lovell & Schofield [13] in the 1980s suggested that the grain size of sea ice is scaled as  $1/N$  in the centrifuge, consistent with the macro length scale. Consideration of the Laplace surface tension equation:

$$p_1 - p_2 = 2 \frac{\gamma_{12}}{r_{12}}$$

where  $p_1$  and  $p_2$  are the pressures of the two phases (ice and water),  $\gamma_{12}$  is the surface tension on the interface between phases and  $r_{12}$  is the mean radius of curvature of the interface, however, suggests that as the phase pressures and surface tension are equal in the model and prototype, that the mean radius of curvature should also scale as 1, i.e. in the same way as particle size.

For prototype behavior to be exhibited by the model, it is vital that the size of the ice lenses scales as  $1/N$  as otherwise a non-realistic pattern of lenses will be observed. If one considers the behavior of the soil of the freezing fringe, however, any ice crystals within the pores of the soil

in this zone will block pores and hence drop the permeability of the soil, limiting the flow of water into the lenses, and hence the extent of their growth. If the size of these crystals scales as  $1/N$ , the crystals will be much smaller in relation to the pores than those in the prototype structure and hence one might expect the model to show larger than expected permeability through the frozen fringe and hence larger lens size. If, however, the ice crystals within the pores of the frozen fringe scale as 1, similarity on the micro-scale will be assured and hence permeability will be identical between model and prototype, consistent with the behavior in the rest of the model.

Little information is available on the scaling and importance of the size and rate of growth of ice crystals within voids and hence this is an aspect of the model behavior that should be quantified by modeling of models.

### 9.2 Ice Creep & Fracture

Ice is known to be susceptible to creep deformations under sustained loading. Van Steenis *et al.* [14] report the results of experiments on the creep of floating ice and derive a best-fit material law of:

$$\frac{d\varepsilon}{dt} = 2 \times 10^{-25} \sigma^{3.25}$$

where  $\sigma$  is the applied stress in Pascals and  $d\varepsilon/dt$  is the creep rate per second. This would imply that as the stresses in the model and prototype are identical, the strain rates are also identical and hence the time should be identical in model and prototype. This is obviously in contradiction to the scaling factor on time of  $1/N^2$  used for seepage and thermal behavior within the model.

Creep will be important in redistributing the stresses around the ice lens and will lessen the heave due to lens formation. Nixon [15] performed some numerical studies including the effects of frozen soil creep on the bending moments induced in a pipeline passing from stable to heaving soil. It was found that increasing the creep coefficient from zero to  $6 \times 10^{-9} \text{ kPa}^{-3} \text{ yr}^{-1}$  dropped the induced bending moments in the pipe at the interface between stable and heaving soil by approximately 25%.

Ice is also a brittle material, whose strength is primarily characterized by a fracture toughness, rather than by a yield stress. It was demonstrated by Palmer [16] that the scaling law for the behavior of materials that deform by fracture rather than yield depends on the ratio of the crack size present in the model to that in the prototype. If the crack size is identical in model and prototype, behavior is correctly modeled in a standard centrifuge test, however, if the crack size also decreases from prototype to model, the apparent strength of the material will be greater in the model by the square root of the crack size ratio. Palmer suggests that for brittle materials, 1:N scale models should be tested at  $N^{3/2}$  to achieve identical constitutive behavior.

This is obviously impossible for tests such as those under consideration here where non-brittle materials are also present, but this relationship should be borne in mind when analyzing test results.

### 9.3 Uplift Resistance Mobilization

As discussed in Section 4.1, work carried out by Palmer *et al.* [4] investigated the effect of model scale on the uplift resistance of buried pipelines. Whilst this work did not include freezing ground, the results are still worthy of consideration here. Localized uplift of freezing ground will be governed by equilibrium of the uplift forces due to the formation of ice lenses and the resisting forces due to the self-weight and strength of the overlying soil. Palmer *et al.* showed that whilst the resistance provided against uplift of a pipeline in the centrifuge at 10-g was similar to that found at 1-g, the response in the centrifuge was less stiff, with a similar amount of un-scaled displacement being required to mobilize the full resistance at 10-g as at 1-g.

This result may influence localized frost heave, but as the particle size of frost-heave susceptible soils is in general small, the movements required in order to mobilize full resistance are likely to be small in relation to the soil heave. This should minimize the influence of this error on the results.

## 8. Previous work on Frost Heave

Previous centrifuge studies have been carried out on frost heave, some of which involved modeling of models in order to clarify the applicable scaling laws.

### 8.1 Yang & Goodings [17]

Yang & Goodings [17] carried out a series of 11 centrifuge tests on level beds of silt and silty clay, chilled on the surface with cold air from a vortex tube. The models were tested at three g-levels, 20, 30 & 45-g, with a scale factor of  $1/N^2$  being used for time. It was shown that for models of identical prototypes tested at different g-levels, the ultimate heave deviated by a maximum of 13% from the mean and the depth of frost penetration by a maximum of 9%. Repeatability tests were also carried out and showed a coefficient of variation of around 10% for identical models tested at the same g-level, similar to that found from the modeling of models tests. No pattern of heave with g-level was observed, leading to the conclusion that the scatter was due to experimental error and was not a function of g-level.

Post-test, the models were sectioned in order to investigate the size of ice lenses formed in the tests. It was found that the lenses formed showed a trend of decreasing size and decreasing spacing with increasing g-level. Insufficient data is presented to allow confirmation of the scaling law on ice lens size from this paper.

This work leads to the conclusion that uniform 1-D frost heave can be scaled in the centrifuge.

### 8.2 Ketcham *et al.* [18]

Ketcham *et al.* [18] performed three centrifuge tests at 67, 80 and 100-g in order to investigate the uplift forces on a constrained footing on freezing silt. The test data shows reasonable agreement on the depth of frost penetration, free-field heave and peak uplift force. The time taken to achieve uplift from the beginning of freezing and the shape of the uplift force-time curves, however, show some marked differences. The time to achieve uplift appears to correlate

more closely with model time than with the prototype time, (scaled as  $1/N^2$ ), and the uplift force shows considerably more post-peak softening in lower g-level models than in the 100-g model. This suggests that the frozen soil is creeping allowing stress relaxation. If the creep is occurring with a time scale factor of 1, as suggested in Section 7.2, this fits with the data presented, as the lower g centrifuge tests occur over a longer model time, allowing more creep to occur.

It should be noted that the temperatures of the top and bottom interfaces of the soil layer were not logged during the experiment, the temperatures plotted being the values that the temperature controllers were attempting to achieve. It is not hence known how well the desired temperature profiles were followed and whether this varied with g-level due to the increased heat flux in higher g models.

It should also be noted that as the same reaction frame system was used for the three tests, the prototype vertical stiffness of the foundation system was greater at 100g than at the lower g-levels. This may have influenced the results.

Sections were taken of the models post-test in order to examine the size and distribution of ice lenses. It was concluded that the ice lens pattern in the samples was not geometrically similar in the three tests. In the 100g test, a 3mm thick zone of vertically biased lenses was observed which was progressively less thick in the lower g models. Above this zone horizontally biased lenses were present in the lower g models, which were not visible in the 100-g test.

The results of this work lead to some skepticism of the scaling behavior of frost heave, though the sparseness of instrumentation and the lack of repeated tests makes it impossible to draw robust conclusions about the fundamental scaling behavior of frost heave in the centrifuge.

### 8.3 Phillips *et al.* [19]

Phillips *et al.* [19] present the results of two preliminary demonstration centrifuge tests on frost-heave of buried chilled pipelines and compare the scaled results of these tests with those observed at full-scale in tests conducted by the University of Calgary in 1973-74 (Slusarchuk *et al.* [20]). The scaled results for the first 200 days of prototype operation show good comparison between 30-g and 1-g tests, with a maximum variation of about 20% between centrifuge and 1-g models. Ice lenses were observed by post-test excavation and were seen both circumferentially and radially. It is surmised by the authors that the radial lenses are the result of post-test stress relaxation, whereas the circumferential lenses were formed during the test and caused the uplift of the pipe. The ice lenses were seen to become larger with increasing distance from the pipe, consistent with the work of Konrad [21] who suggests that as the freezing front propagates outwards from the pipe, its rate of growth falls, allowing more water to be drawn in to the developing lenses which hence achieve a greater size.

This work suggests that results representative of those of full-scale experiments can be achieved when modeling frost heave in the centrifuge. Further experiments including modeling of models and repeated tests would give greater confidence in the reliability of these procedures.

## 9. Conclusions

Centrifuge modeling is a valuable tool for the prediction of the behavior of geotechnical structures, especially in areas in which full scale testing is difficult or impossible to achieve. The technique allows the prototype behavior of geotechnical systems to be implied from the behavior of models in which the stress state is made identical by the enhanced gravity field of a centrifuge. Scaling laws for many geotechnical parameters have been derived and discussed, the most important of which is the  $1/N^2$  scaling law for time, which implies that the short-term behavior of a model can predict the long-term behavior of the prototype system.

It has been shown over the last thirty years that when carried out with care and an appreciation of the modeling issues which could distort the results, centrifuge modeling can accurately predict the behavior of full-scale geotechnical systems and can give an important input into the design process.

The theory and previous work conducted on the centrifuge modeling of frost-heave suggest that this is an area with considerable promise, good correlation having been seen between full-scale and centrifuge experiments, (Phillips *et al.* [19]). The scaling of this phenomenon is however not completely understood, with several complex issues including creep and ice crystal growth being not fully resolved. The results of centrifuge tests on the frost-heave of pipelines could give a very valuable insight into this behavior and be developed into a useful design tool, but in order to achieve confidence in the results a validation exercise involving modeling of models and repeated tests should be carried out.

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