GEOLOGICAL SURVEY OF CANADA

OPEN FILE 5004

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

Natural Resources Canada
Ressources naturelles Canada

Canada

GEOLOGICAL SURVEY OF CANADA

OPEN FILE 5004

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

©Her Majesty the Queen in Right of Canada 2004

Available from
Geological Survey of Canada
601 Booth Street
Ottawa, Ontario K1A 0E8

Lawrence, D.E., Smith, S.L. and Burgess, M.M
2005: Frost Heave and Northern Pipelines, state of the art and status of research —three contributing studies,
Geological Survey of Canada, Open File 5004

Open files are products that have not gone through the GSC formal publication process.

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

Margo Burgess and Sharon Smith
Geological Survey of Canada
Natural Resources Canada

March 2005

Acknowledgements

Support for this work was provided by the Department of Indian and Northern Affairs (Headquarters) and the Geological Survey of Canada, Earth Sciences Sector, Natural Resources Canada**.**

Table of contents

Part 1.

SUMMARY

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

by

D.E. Lawrence[1], S.L. Smith[2] and M.M. Burgess[2]

March 2005

1… 221 Clarence St, Ottawa Ont. K1N 5P9

2…Geological Survey of Canada, Earth Sciences Sector, Natural Resources Canada, Ottawa, K1A 0E8

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. **<u>State of the art paper on frost heave – Review of theory and models (Part 2)</u>**
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 the1970s 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.

REFERENCES:

Berger, T.F., 1977: Northern Frontier, Northern Homeland, Report of the Mackenzie Valley Pipeline Inquiry, vol. 1 and 2, Minister of Supply and Services Canada, Ottawa.

C-CORE, 2004: Review of Centrifuge Testing Applicability to Frost Heave, prepared for Geological Survey of Canada, C-CORE Report R-03-094-285, June 2004.

Clark, J. I. & Associates, 2004: Review of Large Scale Northern Pipeline Test Facilities, report No. R-03-19 prepared for Geological Survey of Canada, June 2004.

EBA Engineering Consultants Ltd. 2004: State of the Art Paper on Frost Heave, prepared for Geological Survey of Canada. Project No.1100051, June 2004.

Lawrence, D. E. 2004: Survey of Expert Opinion on Permafrost and Geotechnical Issues for Northern Pipelines, Geological Survey of Canada, Open file 4734, 22 p.

National Energy Board (NEB), 1977: Reasons for decision, Northern Pipelines, vol. 1, 2, & 3, Supply and Services Canada, Cat. No. NE22-1/1977-1-1.

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

Insert EBA report

Part 3.

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

Insert Clark's report

Part 4.

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

Insert C-Core report