Review of Large Scale Northern Pipeline Test Facilities

Final Report

Prepared for:

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Prepared by:

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Geological Survey of Canada

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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.

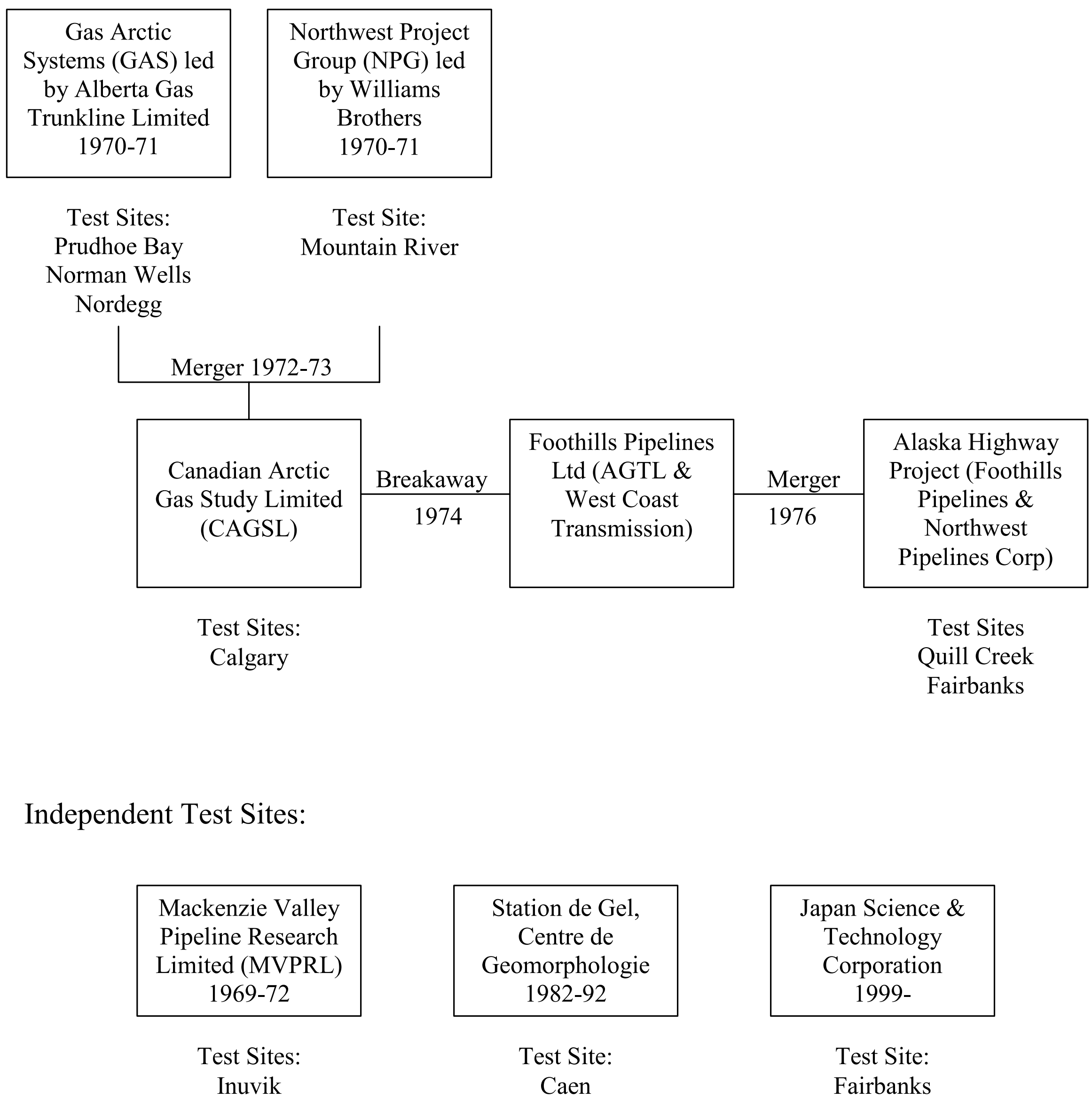


Figure 1: Diagrammatic Representation of Pipeline Proponents and Test Facilities

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.

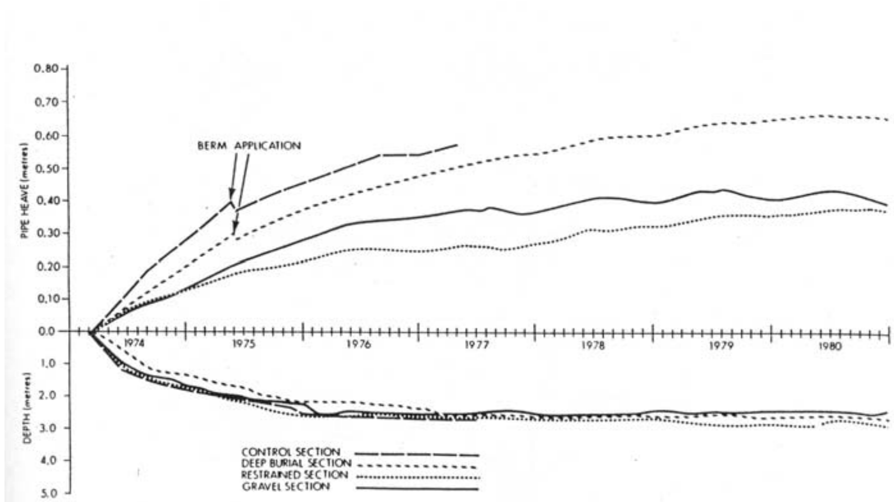


Figure 2: Measured pipeline heave and frost penetration at Calgary test site

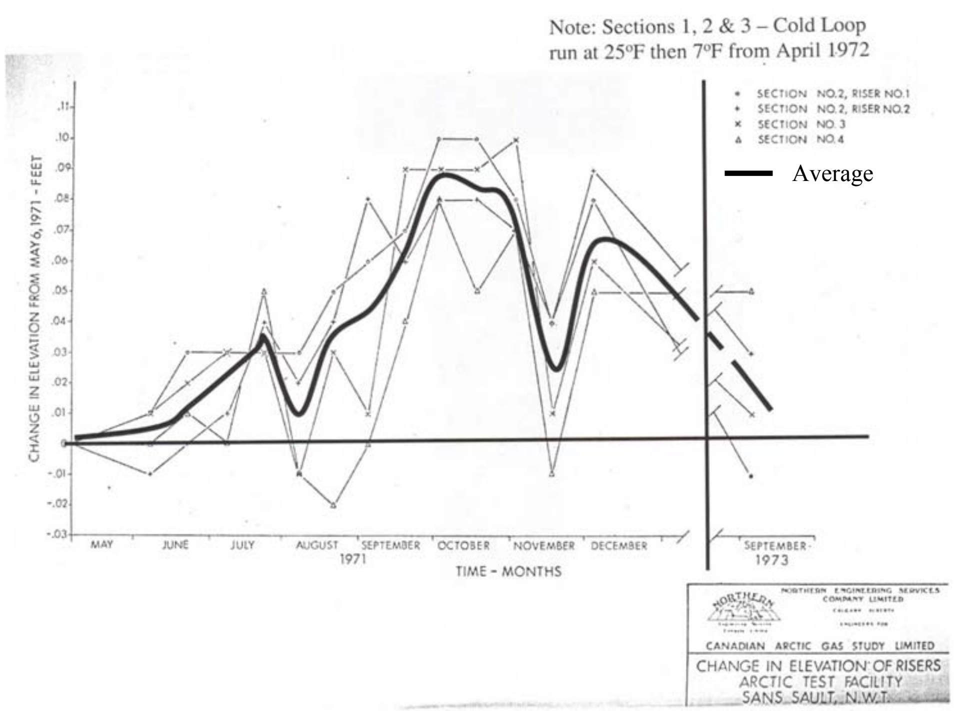


Figure 3: Measured pipe movement at Sans Sault Rapids test site

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.

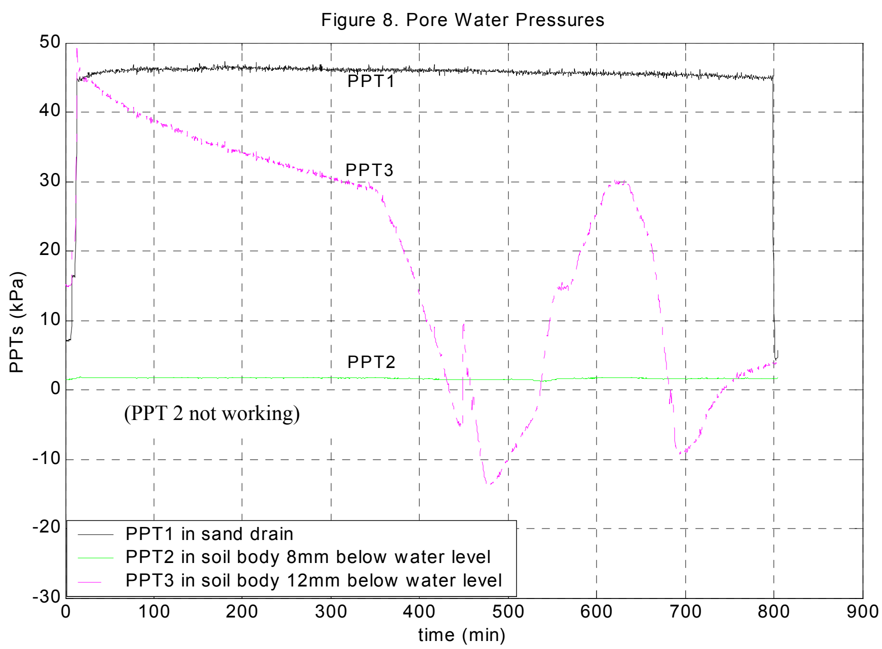


Figure 4: Pore Pressure Response during Progression of the Freezing Front

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.

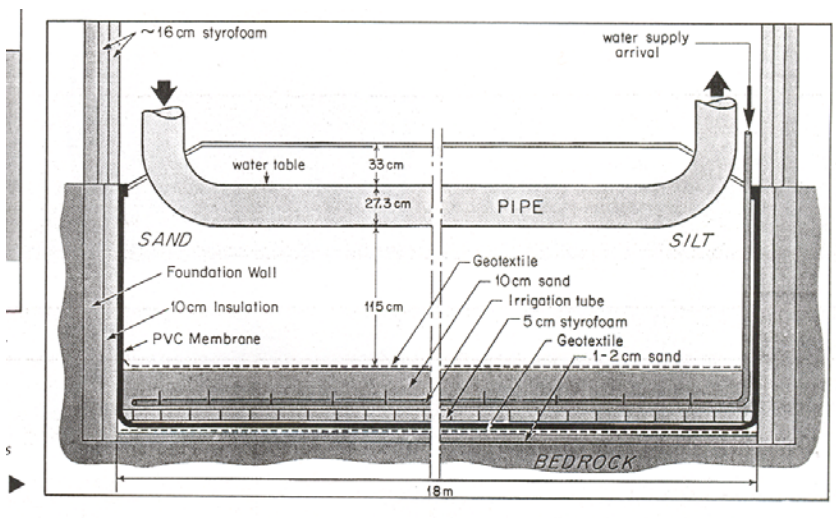


Figure 6: Longitudinal Section of pipe section at Caen, France

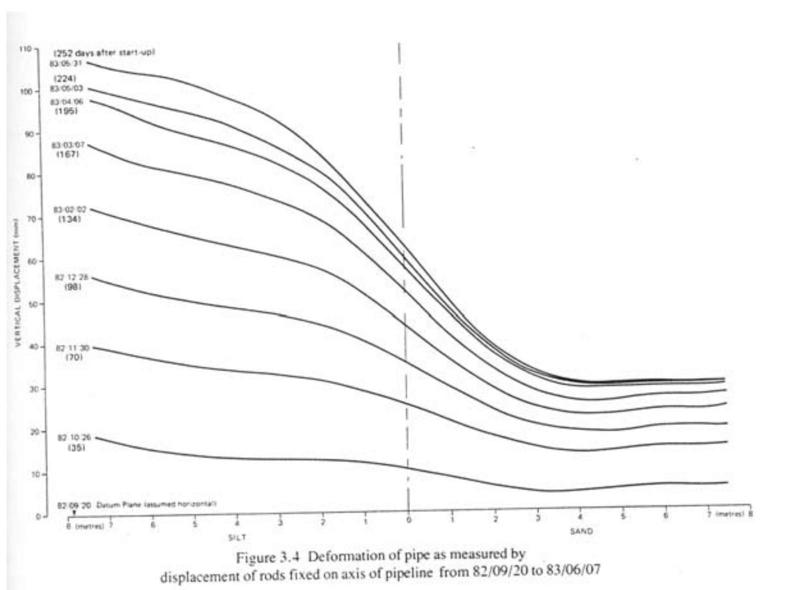


Figure 7: Pipe movement at various times at Caen, France

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.

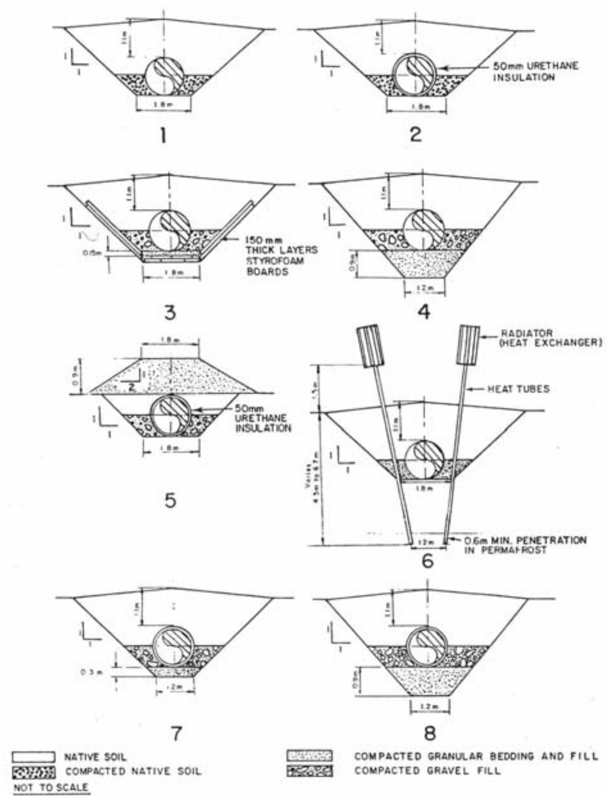


Figure 4 Ditch configurations. Fairbanks frost heave test facility

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.

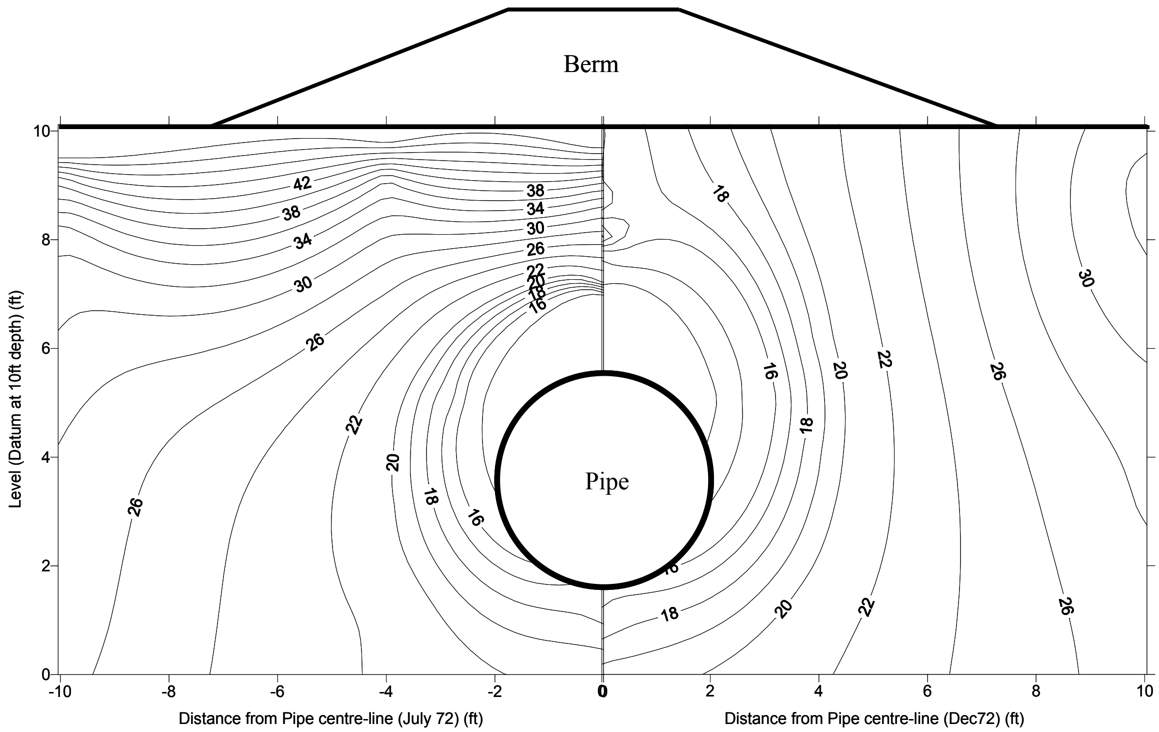


Figure 10: Temperature Contours at Sans Sault Rapids Site

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.

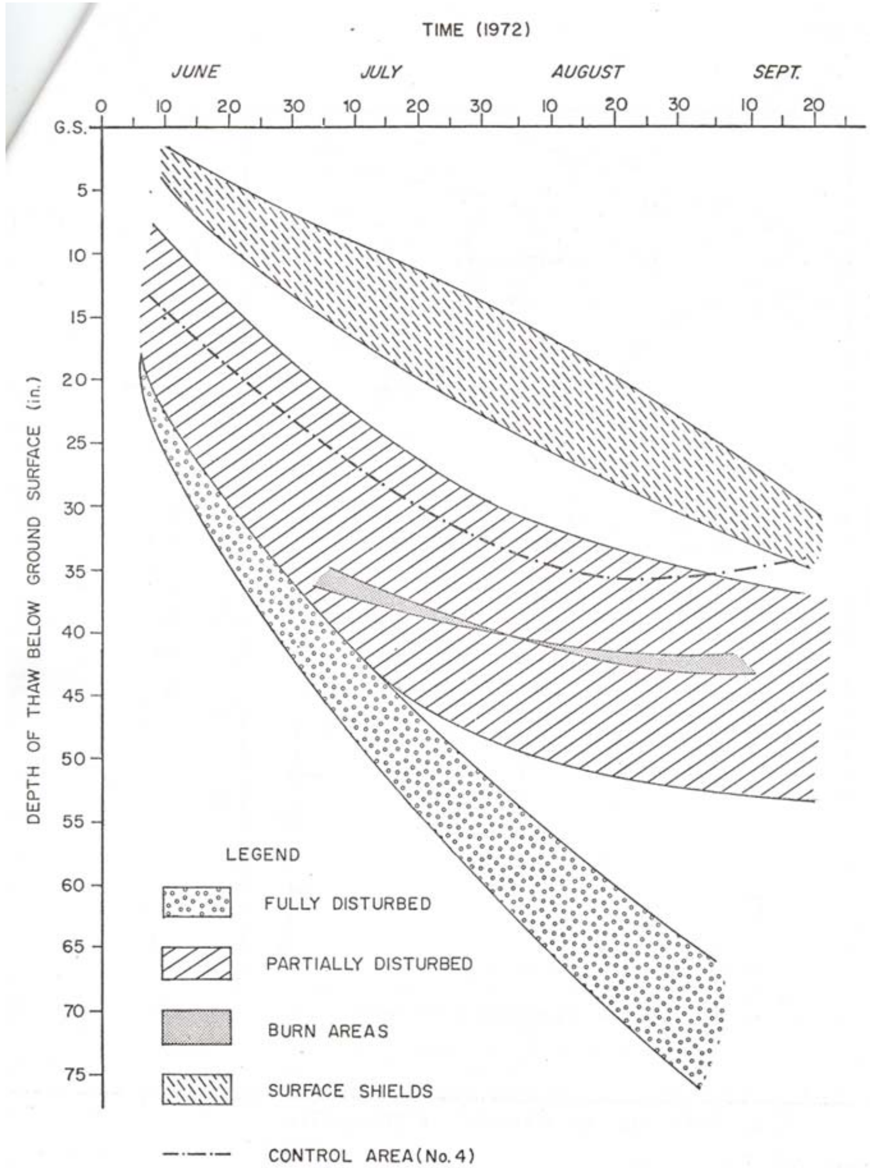
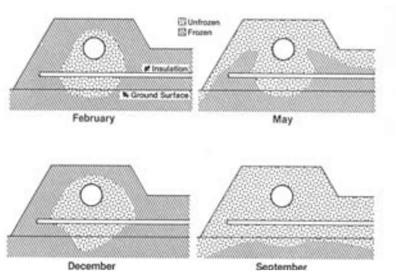


Figure 11: Increase in Active Layer Thickness at Norman Well Test Site

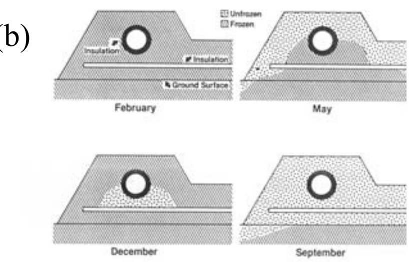
Quill Creek - Very few results published. Thaw settlement for warm gas was primary focus, testing effect of an insulated gravel pad with an uninsulated pipe in a berm, an insulated pipe in berm on an insulated pad and a concrete covered pipe on an insulated gravel pad.

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.

(a)



(b)



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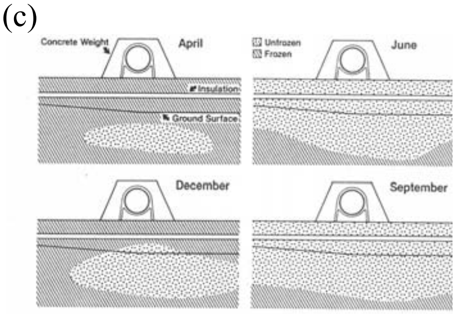

Figure 12: Thermal response for (a) uninsulated pipe in insulated embankment, (b) insulated pipe in insulated embankment, (c) concrete coated pipe on insulated gravel pad at Quill Creek Site

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 superceded 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 10ºC 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, rational 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 errosion 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.