12 Geotechnical Considerations

General Approach

The design, construction and operation procedures for a refrigerated natural gas pipeline in the North are unprecedented and must be novel, effective and economical under exceptionally adverse conditions. At the same time, we must protect the northern environment from any possible permanent damage. Many of the unprecedented aspects are related to geotechnical matters. The existence of permafrost along the pipeline route makes it necessary to depart from the engineering design and construction procedures commonly used by the pipeline industry. Some of these departures involve the innovations discussed in Chapter Three of Volume One.

Geotechnical considerations have a direct bearing on three areas of concern: engineering feasibility, the need for remedial construction on a threatened portion of the pipeline, and environmentally undesirable effects of geotechnically related activities. I shall deal briefly with each of these areas before turning to specific geotechnical problems.

The feasibility issue which, in Volume One, was central to my discussion on engineering and construction of a buried refrigerated gas pipeline in the North, is important because several aspects – including chilling the gas – lack precedent. For example, the pipe is expected to heave differentially as it passes through several hundred miles of discontinuous permafrost. Arctic Gas have undertaken an extensive laboratory and field research program into the phenomenon of this frost heave, and during the Inquiry, the mechanism and extent of the heave was the subject of much debate among many experts. Nevertheless, fundamental differences of opinion remain.

It cannot be said that a gas pipeline cannot be built and operated along the Mackenzie Valley, however, the limits within which the pipeline must be designed and built to ensure acceptable performances have yet to be determined. Some uncertainties will doubtless still exist at the start of construction, and they may be resolved only by observing the pipeline in operation. A comprehensive overview of such aspects of the work will obviously be required.

1. These geotechnical aspects of the proposed project that lack precedent and experience should be independently reviewed by a board of competent experts appointed by the Agency. The board should consist of three experts, such as a permafrost geologist, a cold regions geotechnical engineer and a gas transmission engineer, with specialist advisers available as required on temporary assignment.

The evidence I have heard shows that, because of lack of precedent, important geotechnical engineering decisions have been reached using empirical formulae derived from laboratory tests and the interpretation of site conditions that are not well-known. Schedules have been established on the basis of assessments of situations that are not well-understood. It is important to determine the sensitivity to error of such decisions. For example, towards the end of the hearings, Arctic Gas disclosed that certain testing equipment was faulty, casting doubt on the accuracy of information about feasibility of deep burial and surcharge as a practical method of controlling frost heave.

2. The Company should establish the sensitivity to error of decisions based on empirical formulae and site conditions and evaluations that are not well-known. Where the basis for decision is found to be sensitive to error, its reliability should be established by the use of thorough cross-checking procedures that are satisfactory to the Agency.

My concern with the second issue – remedial construction – relates primarily to the environmental consequences of emergency repairs to the line. If these repairs have to be carried out during spring thaw or at a time of year when wildlife is sensitive to disturbance, they could cause unacceptable damage. For example, the Applicant, using for the most part statistics for the operation of warm gas lines in areas without permafrost, predicted a probable pipeline breakage frequency of once in ten years. Such statistics, however, do not necessarily apply to the operation of refrigerated gas pipelines in permafrost areas: the actual performance may be better or worse. Clearly, the lack of precedent, together with engineering innovation and the possible environmental consequences of untimely repairs make it desirable to use design and monitoring methods that will reduce risks.

3. *The approach to design, construction method and control should be more conservative than is customary in pipeline engineering practice. In particular, the Company should prepare environmental contingency plans to cover a wide range of project conditions that may arise during construction and operation of the pipeline.*

Finally, there are several circumstances that, although acceptable from a geotechnical viewpoint, may be environmentally undesirable. For example, the development of the frost bulb around the refrigerated pipe could, without threatening the pipeline, interrupt drainage and cause terrain damage through permafrost degradation; or it could result in the blockage of low winter flows to downstream pools in creeks where fish overwinter. Although not serious with respect to pipeline operation, the consequences could be environmentally significant.

4. *In order to minimize geotechnically related environmental disturbance, the Company should, before construction, obtain as much data as possible on surface and subsurface conditions. Because of the size of the project and the remoteness of the area, it is inevitable that much important information on geotechnical design will be discovered only during construction. The pipeline design phase shall, therefore, be considered as part of the construction phase, to be terminated only at the end of construction. The Company shall establish a workable liaison between those responsible for design and those responsible for construction, and shall demonstrate, to the satisfaction of the Agency, that all the engineering and environmental implications of the design concept are being carried through into construction.*

5. *Bearing in mind the proposed rapid pace of construction, the Company should establish, in cooperation with the Agency, an appropriate and reliable means of carrying out desirable design changes. Such changes would probably be done by a field design staff, with recourse to the main design office for major design changes only.*

The need for a well-selected and organized field team for inspection and construction control is obvious. Bearing in mind the considerable number of people required on this team, and the seasonal nature of the construction schedule, it will be difficult to find and keep qualified personnel. As I mentioned earlier, the work must be as error-proof as possible by conservative design, but a reliable system for checking the work is also needed.

6. *The Company should establish an educational program to ensure that all geotechnical field personnel fully appreciate the environmental significance of their work.*

The first six recommendations are general, and deal with geotechnical problems in an overview fashion. Given below are descriptions and recommendations on the major geotechnical design aspects: frost heave, slope stability and pipe buoyancy.

A great deal of information on major geotechnical issues was brought before this Inquiry and the National Energy Board; nevertheless, much uncertainty still remains about this critical aspect of the project. I intend to review the evidence so that all parties will know, without laborious research into applications, transcripts, evidence and cross-examination, where the issue stands. I have relied to a great extent on the information in Commission Counsel's final argument and on the subsequent work of my staff in reviewing and updating information. They, of course, referred to the National Energy Board transcripts when doing this.

Frost Heave and Thaw Settlement

One of the most important geotechnical design factors examined during the hearings was frost heave in unfrozen ground, that is, the upward movement of a buried pipeline resulting from freezing. To avoid melting the permafrost, the pipeline companies propose to keep the gas flowing through the pipeline at temperatures below the freezing point of water. However, the permafrost is not continuous, and when the chilled pipeline crosses unfrozen ground freezing would be induced in the soil around the buried pipeline. The frost penetration could, under certain circumstances heave the pipeline in these areas.

A buried refrigerated pipeline through discontinuous permafrost is without precedent. The phenomenon of frost heave applies to a significant length of the proposed pipeline and the control of frost heave is therefore central to the feasibility of the proposed pipeline. The evidence given on frost heave and thaw settlement, as they relate to the construction and operation of the proposed pipeline, reveals that uncertainties still exist in four areas: prediction of frost heave and the effectiveness of the preventive and remedial measures; location of the southern limit of refrigeration; confirmation of design assumptions during construction; and monitoring of frost heave after construction. These four considerations are basic to the geotechnical design of the pipeline, and the resolution of any problems they may cause is essential for an engineering design that is environmentally acceptable.

Prediction of Frost Heave and Effectiveness of Preventive and Remedial Measures

A reliable prediction of frost heave is central to the design of effective frost heave control measures. Attempts to predict the magnitude of frost heave must be based on a complete knowledge of the freezing processes involved. As I described in Volume One, a full understanding of these processes does not appear to exist.

To study the frost heave phenomenon, Arctic Gas carried out a series of laboratory tests and a full-scale field test in Calgary. From these tests they derived a set of empirical equations that they believe encompass the signficant parameters governing frost heave. Their study reveals that the growth of ice lenses where frozen and unfrozen ground meet is governed, in part, by the effective stress in the soils at that location. Once a critical effective stress – the shut-off pressure – is reached, the ice lenses will not grow at the frost front, and the problem of heave is considered solved. Because the shut-off pressure varies with soil type, Arctic Gas determined its value for the range of soils likely to be encountered along the route of the pipeline.

Although heave is the central phenomenon, it is differential heave, – that is, the relative heave of adjacent locations with different soil properties – that requires most attention when considering the adverse effects of heave on the pipeline. A parametric study carried out by Arctic Gas indicated that the time to reach the point at which differential heave became critical, that is, at which rupture of the pipe would occur, is a function of length of heave section, and of the uplift resistance of the frozen ground at each end of the heave section. The study indicated that the minimum time to rupture, assuming frost heave is not controlled, ranges from about eight months to several years. Assuming that the empirical method for predicting frost heave and shut-off pressures is valid, the study concluded that increasing the effective stress at the frost front would be an effective technique for keeping differential heave within acceptable limits.

Based on this understanding of the frost heave problem, both Arctic Gas and Foothills proposed two techniques to limit the effects of frost heave: first, surcharge the ground surface with an earthen berm so that the overburden pressure at the frost front below the pipe approaches the shut-off pressure; secondly, bury the pipe deeper so that higher effective pressures are achieved at the frost front. For special circumstances, and as contingency measures, they proposed a number of other techniques: the excavation and replacement of frost susceptible material; the use of insulation around the pipe, along with granular backfill below the insulation; dual pipelines at river crossings so that gas flow can be run alternatively between each pipe; local increase in the temperature of the gas to relieve the stresses from frost heave; localized freezing to accelerate the growth of the frost bulb so that the frost front beneath the pipe penetrates rapidly to a depth where the overburden pressure is close to the shut-off pressure; and use of slip joints or pliant clay around the pipe to reduce pipe stresses where critical differential heave is anticipated.

Arctic Gas concluded from their test data that the maximum shut-off pressure in the field would be in the range of 4,000 to 5,000 pounds per square foot (psf) and the primary mitigative measures would include either deep burial, or a non-erodable surcharge berm with maximum height of about 10 feet or some combination of both measures, to limit the heaving to an amount acceptable from engineering and environmental viewpoints. They also indicated that berm heights of over 11 feet, and burial deeper than 15 feet, were impractical.

Arctic Gas and Foothills said that, before construction, they will identify areas of potential frost heave along the route and decide on specific measures to limit it. For this purpose, they have characterized the potential for frost heaving of a number of terrain types. They also propose to determine the distribution of unfrozen soils along the route by geophysical profiling immediately after right-of-way clearing. Arctic Gas claim that their geophysical profiling has successfully distinguished between frozen and unfrozen ground.

On October 7, 1976, Northern Engineering Services, engineering consultants to Arctic Gas, informed both this Inquiry and the National Energy Board of a previously undetected leak in their laboratory test equipment. This flaw seriously affects the validity of the test results used to predict the shut-off pressures for various soil types. In their evidence, Northern Engineering Services stated that the shut-off pressures may exceed 7,000-10,000 psf, which is significantly higher than their initial estimate.

In February 1977, Arctic Gas filed with the National Energy Board information regarding their plans for controlling frost heave. In this evidence they conceded that, for virtually all soils to be crossed by the refrigerated pipeline, the depth of burial and the height of berm required to control frost heave would exceed practical limits. Moreover, Arctic Gas indicated, for the first time, that frost heave would be a problem where the pipe passes through shallow permaforst.

According to the new plans presented with the foregoing evidence, insulated pipe with heat trace would be used in all overland sections where the ground is unfrozen, or where permafrost is less then 15 feet thick. Heat probes would be used to prevent the build-up of ice lenses where permafrost is 15 feet or more thick. At river crossings in frost susceptible soils, a heavy casing would be placed around the insulated pipe and heating cables would also be used. Foothills, on the other hand, propose to use insulation, with replacement of frost susceptible materials, to control frost heave. There are, however, no experimental or field observations to confirm that Foothills' approach will work.

A review of all available evidence reveals a number of uncertainties and concerns. First, it is apparent that the phenomenon of frost heave is not well-understood, and that a reliable prediction of frost heave magnitude under various terrain conditions is not yet possible. The major redesign of frost heave mitigative measures by Arctic Gas during the hearings reflects this problem. An erroneous prediction resulted in an unsuitable initial design.

The absence of empirical verification of frost heave predictive methods, the lack of information on the behaviour of pipeline insulating materials, and the lack of precedent for frost heave under operating conditions make it difficult to examine the effectiveness of the redesigned mitigative measures, including insulation and heat tracing, proposed by Arctic Gas. There is also some concern about the environmental effect of the extensive overhead electrical transmission system required for heat tracing. However, the criteria for redesign of frost heave mitigative measures focus on the elimination of frost heave in most areas, which appears to be a prudent approach at this time.

Performance of the insulated pipe proposed by Foothills is particularly sensitive to design errors and standards of construction. The design philosophy is to limit the penetration of the frost front to a depth of about 2.5 feet below the insulation, and, where necessary, to replace the frost susceptible soil within this depth with non-frost susceptible material. Should the frost front penetrate beyond this depth and into frost susceptible material, the resulting total and differential heave, because of relatively low overburden pressure and close proximity to the pipe, could be greater than would have been experienced without insulation. The initial performance of such a pipe could be deceptive in that it may take several years for heave problems to develop; once started, however, they could advance rapidly.

To date, insufficient information exists on where critical conditions for differential heave will be encountered in the field. It is uncertain if the worst conditions were understood and allowed for in the analysis. In extreme cases, lack of information could result in increased maintenance over the life of the pipeline, with attendant environmental implications.

Furthermore, no full-scale tests have been carried out to assess the problem of differential heave. The Calgary field tests were conducted in nearly homogeneous soils, and total heave only was measured. Evidence presented at the Inquiry revealed a concern that the developing frost bulb in the prototype would have both strong and weak sections, depending upon the heterogeneity of the surrounding soil, and that any pipe deformations would be concentrated in the weak sections. The concern is apparently unresolved at this time.

Although it is generally agreed that ice lensing and heave can occur in soil already frozen, that is, behind the frost front, as well as in soil as it freezes, experts disagree on whether or not this phenomenon is of engineering significance to the pipeline over the long term. The study of water migration in frozen soils is a new area of research, and the disagreement results in part from a lack of scientific knowledge.

7. *Because the issues involved in the geotechnical aspects of the engineering and construction of the pipeline are unprecedented, and because the detailed experience gained by those associated with the Mackenzie Valley Pipeline is unusually valuable both in itself and as a base for further necessary investigations and studies, the Company and the Agency should make a sincere effort to use the existing expertise. At the same time, the Inquiry has shown the merits of new and independent appraisal, and this should be encouraged throughout the geotechnical design and review process.*

8. *The Company should adopt an approach to unprecedented geotechnical issues that will ensure a suitably conservative design. In particular, the design and construction contract arrangements for the project should be flexible enough to permit substantial changes as more understanding is acquired of geotechnical conditions and techniques.*

9. *Emphasis should be placed now on further theoretical and field investigation into the effectiveness of insulation plus heat tracing in controlling frost heave.*

10. *The field drilling program and geophysical profiling should be completed before the final design phase. Detailed subsurface investigations should be carried out at locations typical of those where severe differential heave is anticipated.*

The Location of the Southern Limit of Refrigeration

The main reason for refrigerating the gas below the freezing point of water is to prevent permafrost regression and associated environmental and thaw-settlement problems. In northern areas where the pipeline passes through predominantly ice-rich permafrost, potential problems caused by thawing of the ground are a more serious consideration than any problems that could arise from frost heave in occasional segments of unfrozen ground. In such areas, the merit of chilling the gas is obvious. In the southern part of the discontinuous permafrost zone, however, the amount of unfrozen material along the pipeline route increases to the point where potential problems from frost heaving are more serious than problems associated with the thawing of permafrost. Therefore, it is necessary to establish a geographic limit for refrigeration that is, in effect, a trade-off between the problems caused by chilling and the problems caused by thawing of permafrost.

A final decision on the location of the limit of chilled gas transmission is difficult to make. During the Inquiry, Arctic Gas changed their southern limit, which meant that the gas temperature would have remained below freezing to a point approximately 50 miles south of the Northwest Territories–Alberta border. Following the discovery of the flaw in their freezing test apparatus, Arctic Gas again moved the southern limit of refrigeration, this time to a point north of Fort Simpson. This change meant that the section south of Fort Simpson would be kept above rather than below freezing, and any permafrost encountered would be thawed. To maintain pipe stability where this thawing occurs, Arctic Gas proposed deep burial of the pipe; and, in critical locations, they proposed supporting the buried pipe on piles fixed in stable material beneath the thawed area.

Foothills reported that their tentative location for the limit of chilling is just southeast of Fort Simpson. Drilling and terrain analysis from this point towards the Alberta border for a distance of approximately 100 miles indicates that one-third of the route is in permafrost. Some of this permafrost can be expected to have high ice content and, therefore, to be thaw unstable. Foothills' consultants, and the National Energy Board have concluded that additional exploration work is necessary before a final design for thaw settlement is prepared.

A review of the evidence indicates to me that neither pipeline company has sufficient field information on which to base a final decision on the best location for a southern limit of chilling. Sufficient information may not be available until construction begins and evidence is obtained from an examination of the trench walls. Furthermore, the two companies have not developed a "trade-off" approach that will mitigate the adverse effects of chilling and not chilling. Although they investigated the problems of chilling, Arctic Gas have not thoroughly investigated the problems resulting from thaw settlement. There is evidence that problems resulting from permafrost thaw could occur over a longer period of time, and hence involve greater maintenance than those problems associated with frost heave. As well, surface ponding caused by settlement could result in thaw conditions more adverse than those predicted. For this reason, a wrong choice for the southern limit of chilling would increase the need for maintenance and thus the environmental impact.

11. *Areas where significant thaw settlement and frost heave could occur should be reliably identified by the Company. Before construction, measures for reducing the impact of thaw settlement should be studied in detail and submitted to the Agency for approval. Where necessary to resolve technical problems related to frost heave and thaw settlement, the Company should conduct supporting field tests to the satisfaction of the Agency.*

12. *Based on detailed field studies, the Company should use conservative design practices to select a tentative southern limit of refrigeration. This limit is a location south of which the need for cooling equipment is considered remote, using thaw settlement designs with a high factor of safety. If necessary a final decision on the location of the limit of chilling should be postponed until construction, when additional detailed soils data will be available.*

13. *The design of the cooling equipment should be such that the location of the southern limit of gas cooled below 0°C can be modified, depending upon the behaviour of the pipeline when in operation.*

Confirmation of Design Assumptions During Construction

Arctic Gas planned to prepare design manuals and tables that will specify the mitigative measures required for site-specific features such as terrain type and line temperature. Because it is impossible to anticipate all terrain conditions, they propose a design-change manual that will be available before construction begins. This manual is intended to cover most of the changes found necessary because actual conditions differ significantly from those anticipated before the start of construction.

As I said earlier, Arctic Gas intended to identify those locations where permafrost is not present by undertaking geophysical profiling shortly after the pipeline right-of-way has been cleared. They also intended to catalogue permafrost and soil conditions adjacent to and along the right-of-way, and to record, on a mile-by-mile basis, geotechnical conditions in the ditchwall. The frequency of recorded observations in the ditch will be determined by the natural variability of conditions and potentially troublesome sections.

Under the schedule proposed by Arctic Gas, the pipeline would be constructed in three winter seasons, each season being three to five months long. During each winter season, they propose to construct a maximum of 450 miles of pipeline in three spreads in the discontinuous permafrost area. Thus, an average of some 3.75 miles of pipeline per day are to be inspected; problem areas will be identified and appropriate design changes implemented by experienced geotechnical inspectors.

With the rapid pace of construction, it may be difficult to ensure that all geotechnical problem areas are detected and adequately dealt with. Even an examination of the ditch walls may not be sufficient. While the mile-by-mile inspection of the ditch will be helpful, it will not indicate the nature of the soil below the bottom of the ditch. The presence of frost susceptible material may not be established during construction. Furthermore, very highly experienced personnel may have difficulty identifying the nature of frozen soils in a trench wall. Finally, it may be difficult to meet the demand for experienced geotechnical inspectors. For these reasons, frozen soils, frost susceptible material, and areas of differential heave and thaw settlement may go undetected.

14. *The Company should demonstrate, well in advance of construction, how it proposes to cope with the problem of selecting, organizing and administering construction control and inspection personnel.* (See Project Regulation and Review.)

15. *The Company should have on site, as the work proceeds, an adequate team of geotechnical personnel with the appropriate experience to make decisions on the need for design modifications or for further investigation. This team should be efficiently organized and have a working arrangement with* *contractors that will ensure prompt implementation of the correct design modifications.*

16. *Before final design, the Company should demonstrate to the Agency that its investigations of soil conditions along the route have been sufficiently detailed to permit the preparation of a design that is reliable and that would require a minimum of changes in the field. The design engineers should develop a systematic feedback of data from the geotechnical field inspector's logging during construction to confirm previous exploration of soil conditions and the site-specific design measures.*

17. *To ensure that there is a satisfactory mechanism for the prompt identification of problem areas and implementation of design changes, an independent review of the field organization for engineering supervision and construction control should be undertaken periodically by the Agency as construction proceeds.*

Monitoring of Frost Heave After Construction

Both Arctic Gas and Foothills stated that they will monitor the pipeline in all areas where frost heave may occur, and Arctic Gas will also monitor all areas south of the limit of refrigeration where frozen soils may thaw.

To measure pipe curvature, Arctic Gas intended to use inclinometers or settlement profilers at river crossings, and risers or other conventional survey techniques in overland areas. They also intended to check the pipeline visually at regular intervals and to use aerial photographs. They estimate that extensive monitoring of frost heave would be required over a 400-mile length, although this calculation may now have changed because of their frost heave redesign.

Because most differential heave will normally occur in the initial years of operation, both pipeline companies recognize that frequent monitoring may be required during these years. The proposed methods of pipeline monitoring may not be suitable for the frequency of observation that may be required during the initial year or two of operation. Some sections of the pipeline may require monitoring monthly. Visual inspections and surveying risers are not only time-consuming and potentially difficult in winter months, they may not detect all locations where differential heave is causing significant change in pipe curvature. If monitoring is not effective or if it is not carried out frequently enough, problem areas may develop undetected, or with insufficient lead time to plan permanent remedial measures. Thus emergency situations may arise, with associated environmental problems.

18. *The performance of the pipe should be monitored by the Company on a routine basis in accordance with a schedule approved by the Agency. This schedule should allow for frequent inspections during the first years of operation, with the frequency of monitoring reduced thereafter, depending on the observed behaviour.*

19. *A study of alternate methods for monitoring the performance of the pipeline, particularly those methods that are feasible for frequent observations, should be carried out by the Company to the satisfaction of the Agency. The use of an instrumented "smart pig," a device that can detect changes in pipe curvature at frequent intervals, is an especially promising alternative and should be given a high priority.*

20. *Because the monitoring program is without precedent, and because it is an important aspect of the project from an engineering and environmental point of view, both the intended procedure and the results of the program should be thoroughly reviewed and approved by the Agency.*

Slope Stability

Slope stability problems involve complex geotechnical considerations that were discussed in some detail at the Inquiry. For the purposes of this report, slope failures in permafrost soils are divided into two categories: shallow failures involving thawed soils, and deep-seated failures involving frozen and thawed soils.

Typical of shallow failures are skin flows, which involve movement of the active layer – the zone of soil above the permafrost that freezes and thaws seasonally – over the top of the permafrost. Skin flows occur in many types of terrain and can be caused by even minor disturbances, such as clearing of the right-of-way. They may also occur in the backfill placed above buried pipe in sloping ground. Arctic Gas stated: "While this type of landslide cannot immediately threaten the integrity of the pipeline, it has been studied in considerable detail because, if left unchecked, unsafe conditions may develop after several thaw seasons" (Northern Engineering Services Co. Ltd., *Some Aspects of Natural Slope Stability in Permafrost in Relation to the Applicants' Proposed Pipeline*, 1974, p. 3).

Deep-seated slides involve displacement of a large mass in the form of blocks of relatively intact material. In the Mackenzie Valley, these slides have affected slopes in the range of 100 to 260 feet high, with an overall slope angle after failure of 9.5° to 20°. Such a large slope failure on the pipeline right-of-way would likely lead to breakage of the pipe.

Creep of frozen soils is a form of slope movement not normally categorized as slope failure. It involves the downhill movement of relatively intact material at a very slow rate.

21. *In deciding on the pipeline right-of-way alignment and any subsequent changes that may become necessary during construction, the Company shall avoid, wherever possible, areas of questionable slope stability. Before construction, the Company shall demonstrate, to the satisfaction of the Agency, that it has undertaken adequate field surveys of the route to ensure the identification of unstable areas that might be* *affected by project activities and that the necessary mitigative measures have been developed.*

A review of the available slope stability information indicates four broad areas of concern: prediction of flow slide activity; behaviour of deep-seated landslides; effect of interference of subsurface drainage; and creep of ice-rich slopes.

Flow Slide Activity

Skin flows will likely be the common form of slope instability to occur along the pipeline right-of-way. Both Arctic Gas and Foothills have stated that the direct geotechnical and environmental implications of skin flow failures are not severe. However, if these failures should occur to a greater degree than anticipated, and if they are left untreated, additional permafrost regression and subsidence may occur and significant erosion could develop as a result of surface run-off.

Arctic Gas stated that "skin flows can occur for a wide variety of reasons but recent research has stressed the dominant influence of thawing in promoting instability" (Canadian Arctic Gas Pipeline Ltd., *Responses to National Energy Board for Additional Information*, Vol. V, No. 4, Q. 8, p. 4). Accordingly, they have developed a method of analysis based upon the theory of thaw-consolidation. This theory is concerned with the development of excess water pressure in the pores of a thawing soil; it considers the rate at which water is produced by thaw with the rate at which water can be squeezed out of the thawed soil. Excess pore water pressures can result in slope failures. For the purpose of analysis, a slope stability equation was developed to permit computation of the factor of safety against sliding. Although Arctic Gas recognizes other mechanisms that also control skin flows, they have not evaluated them in detail.

By using the slope stability equation and the theory behind it, Arctic Gas intend to identify all potential areas of flow, slide or backfill instability. This equation is also basic to the design of the proposed stabilization measures, and if this equation does not correctly predict actual field behaviour, numerous areas of instability may appear unexpectedly. The slope stability equation is based on the thaw-consolidation theory. Although this theory is supported by valid reasoning and laboratory research, there is only one well-documented case history, which is contained in "An Analysis of the Performance of a Warm-Oil Pipeline in Permafrost, Inuvik, N.W.T." by Morgenstern and Nixon. The authors conclude: "Clearly many more well-documented case histories are required for differing soil and thermal conditions to increase the level of confidence in the application of the theory" (p. 208).

Foothills have challenged the approach taken by Arctic Gas. They argue that the natural variability of the parameters required in the thaw-consolidation theory can be so great as to render the theory unreliable and of doubtful practical value. Other witnesses before the Inquiry expressed similar criticisms. Foothills have emphasized field observation and measurement of actual pore pressures, but have not carried out sufficient field work to demonstrate the practicability of their approach.

22. *The Company should conduct detailed field studies on a number of selected flow slides to consider the effect of variation in topography, slide geometry, soil type and cause. The purpose of this work should be to clarify and extend understanding of flow slide mechanisms in relation to the construction and operation of the pipeline.*

23. *The Company should develop a plan for reliably detecting the occurrence of flow slides along and adjacent to the pipeline right-of-way. Monitoring during construction and operation should be carried out by Company experts experienced in the investigation and assessment of slope stability hazards in permafrost terrain.*

The Behaviour of Deep-seated Landslides

The pipeline route crosses several relatively high, steep slopes, usually at river crossings where there is a possibility that a large, deep-seated slope failure may occur. Arctic Gas identify 33 slopes that are higher than 100 feet and have slope angles greater than 9°. They believe that not all 33 slopes are susceptible to deep-seated failure, because other factors that they consider to be necessary for failure are absent.

The stability of these slopes is assessed using the same basic geotechnical techniques and principles employed in non-permafrost areas. Some modification of these principles is required where the ground is completely or partially frozen. A number of the aspects of deep-seated landslides in permafrost areas are not well-understood, and their behaviour is apparently unique to frozen ground. In particular, uncertainty exists about the magnitude of available strength along potential failure surfaces within frozen ground, and the role of potentially high pore pressures at the permafrost base.

There are no well-documented case histories. The only published analysis of such a slide is found in "The Stability of Slopes in Frozen Soil, Mackenzie Valley, N.W.T." by McRoberts and Morgenstern, and it is based on circumstantial evidence about the soil and thermal condition of the materials actually involved in the slide; as well it lacks topographic data and pore pressure measurements. McRoberts and Morgenstern concluded;

> Geomorphological evidence and experience during drilling at a slide on the Mountain River suggest that substantial pore pressures exist within the unfrozen materials beneath the permafrost. Unfortunately attempts to measure these pore pressures have not been successful and data obtained in the future will be of considerable value in this regard. [p. 572]

Although the preliminary studies conducted by Arctic Gas and their consultants indicate that the deep-seated failure mode can be successfully analyzed using the approach indicated, definite conclusions regarding the reliability of the approach must await the collection of more field evidence. If a critical condition is overlooked, either because field data are inadequate, or because the failure mechanisms are not fully understood, the ensuing landslide would lead to engineering and environmental problems. A large landslide, which could occur rapidly and without apparent warning, might result in emergency repairs with attendant environmental damage.

24. The Company shall investigate and analyze in detail every slope along the right-of-way with a potential for deep-seated instability. Such slopes should be selected conservatively to ensure that potential failure areas have not been overlooked. Because of the lack of detailed investigations of deep-seated landslides involving frozen material, geotechnical investigations to assess the stability of the higher slopes along the route should be more intensive than those normally undertaken for similar situations in non-permafrost areas.

25. Because of the lack of precedent in analyzing high, steep slopes involving frozen materials, the design for any protective or remedial measures such as berming should involve a higher safety factor and a generally more conservative design than is usual for non-permafrost areas.

Effect of Interference of Subsurface Drainage

Where the chilled pipeline crosses slopes in non-permafrost areas, the frost bulb will disrupt the natural subsurface flow of water. It is conceivable that, under some conditions, especially where the pipeline is on a cross slope, the presence of the frost bulb could cause a significant increase in water pressures upslope from the pipeline. Any resultant landslide would tend to occur unexpectedly, and the slide could be large enough to threaten the integrity of the pipe or to cause environmental problems. Emergency measures may also be required, with their attendant environmental problems.

The possibility of slope failures that result from interference with subsurface drainage has not been adequately considered by either pipeline company.

26. The Company shall design and test the feasibility of methods for relieving subsurface water pressures on the uphill side of the frost bulb. During construction, geotechnical field personnel should be aware of this potential hazard. Evidence of significant subsurface seepage adjacent to the right-of-way should be reported, and protective measures should be implemented as required.

Creep of Ice-rich Slopes

Although initial theoretical work indicates that, under some circumstances, ice-rich permafrost soils on slopes can creep a significant amount over a number of years, there is little evidence to show whether or not this acutally takes place in the field. It is recognized, however, that the creep would probably be most significant on the steeper slopes or soils that have a relatively high ice content. Creep may thus be an important consideration at only a limited number of locations.

Creep movements, if they do occur, would likely proceed at a relatively slow rate. It is probable, therefore, that suitable field instrumentation could detect such movements at an early stage and suitable remedial measures could be implemented before the pipeline is affected.

Arctic Gas believe that creep would likely not be a significant factor affecting the pipeline: nevertheless, they have proposed a number of methods to overcome the problem if it should occur. In 1975, they initiated a testing program to determine the creep properties of a range of frozen soils. Other studies done previously were reportedly carried out at higher stress levels than would be encountered on the pipeline. The purpose of the testing program is to provide data for "less conservative final designs" (Canadian Arctic Gas Pipeline Ltd. "Written Direct Testimony, Phase 1A, National Energy Board Hearing," Exhibit N-AG-3-81, Sec. 4, p. 12).

The two pipeline companies have not stated how they would identify areas where significant creep might be anticipated. Given the lack of field information on the creep behaviour of ice-rich slopes, it is unlikely that any reliable method to anticipate creep now exists. Arctic Gas have recognized the need for designs to combat slope creep, but they have so far discussed only concepts; and no specific data exist on the effectiveness of these concepts.

27. The Company's research into the creep of ice-rich slopes should continue until the Agency feels that sufficient information exists to make a confident engineering prediction of those slopes with a potential for significant creep movements.

28. A detailed annual inspection of all slopes that may be unstable shall be included in the postconstruction monitoring program. In their monitoring, the Company shall make use of slope instrumentation techniques acceptable to the Agency.

Pipe Uplift Problems Unrelated to Freezing

The pipeline companies considered two potential causes of pipe uplift not related to chilling of the gas: buoyancy, and pipe stresses that result from the thermal expansion of the pipe and from the high gas pressure.

An analysis of Arctic Gas alignment sheets indicates that a potential buoyancy problem may exist along 44 percent – at most – of the route from Richard's Island to the Alberta border. In non-permafrost terrain, buoyancy problems may occur in rivers, open bodies of water, muskegs, peat swamps and low-lying flat areas that have a high water table. In permafrost terrain, additional buoyancy problems may occur in beaded streams, thermokarst ponds and ice-rich slopes. As identified by Arctic Gas, the three basic conditions under which buoyancy could occur are: open water flotation, for example, water crossings or wherever free water is encountered in the ditch; delayed flotation following natural flooding of a backfilled ditch where there is inadequate resistance to uplift; and pipe flotation following the melting of permafrost in silty or organic soils that have a high ice content.

In their application, Arctic Gas listed seven methods of restraining buoyant pipe; nevertheless, they have stated that, except for open water areas, they will rely as much as possible on deep burial of the pipeline. They intend to make limited use of anchors.

There are basically three consequences of uplift due to buoyancy. Uplift before pipeline start-up will interfere with the schedule; uplift south of the limit of chilling, during operation, may interrupt surface drainage and necessitate the mobilization of a substantial work force and a temporary shut-down of the pipeline; finally, uplift after abandonment would interrupt surface drainage with its attendant environmental problems.

Uplift due to stresses in the pipe, induced by temperature changes and high gas pressure, can occur where the pipe bends, but it is a particular concern at overbends – perpendicular bends in the pipe, such as at the top of a hill. Although a very real problem, the portion of the pipeline likely to be affected is believed to be considerably less than the portion affected by flotation. Uplift from this cause could affect the construction schedule and interrupt surface drainage.

Design of Control Measures

Pipe flotation problems are a well-known difficulty in the pipeline industry. I was told about a portion of the Pointed Mountain Pipeline located in muskeg that floated in the first year after completion of the pipeline: the saddle weights had slipped off the pipe. A group of Canadian experts that included members of my staff visited the Soviet Union in October 1975, and in Northern Russia they observed sections of large diameter pipeline floating with inadequate weights.

The problem of re-installing an uplifted or floating pipe is a serious one, and Arctic Gas have stated that they intend to avoid the problem by taking a conservative design approach; they are depending primarily on burial to control overland buoyancy problems. The selection of design value for the submerged unit weight of the backfill placed over the pipe is a critical aspect of the present design approach. For backfill soils with submerged unit weight in the 20 to 40 pounds per cubic foot range – a range that is common – the size of the backfill mound and its integrity, particularly with regard to erosion of the mounds and slumping of ice-rich backfill, are critical. A design approach vulnerable to change in field conditions may cause frequent pipe flotations in areas where soil conditions differ only moderately from those assumed during design. In view of this, Arctic Gas' safety factor of 1.25 is probably too low.

It is also apparent that some backfill soils will thaw and behave as a thick slurry. This problem may go unrecognized when the soil is in the frozen state. The work Northern Engineering Services carried out for Arctic Gas in August 1974 (*Depth of Overburden Cover over the Pipe and Pipe Anchorage, Technical and Cost Considerations*) is not applicable because it would lead to a result on the unsafe side.

It is important to bear in mind that pipe flotation normally occurs during thaw seasons. This means that, if emergency repairs became necessary, they would have to be carried out during a period that is usually difficult from a logistics and environmental standpoint.

Although the potential for pipe flotation could be severe south of the limit of refrigeration, neither pipeline company has investigated this aspect in any detail. Most of their work has involved the potential for uplift before start-up north of the limit of chilling.

Although uplift and exposure of the pipeline could pose serious engineering problems, in some areas towards the south it may be possible, from an engineering standpoint, to tolerate an uplift condition. However, there may well be unacceptable environmental ramifications if the condition goes unattended for any length of time.

The design of field pipe bends must take into account unprecedented gas pressures and thermal conditions in a large diameter pipe. Faulty pipe bends, if not identified during pressure testing, will likely become evident immediately upon start-up. The risk of problems developing from this source should lessen after start-up.

29. *The Company should conduct detailed drilling and route investigations to identify the location of those areas requiring uplift control measures not related to freezing, and to determine the most suitable design. In particular, uplift due to buoyancy should be taken into account when selecting the southern limit of chilling.*

30. *Greater emphasis should be placed on the depth of pipe buried in areas subject to uplift caused by buoyancy. The cost-benefit approach initiated by Arctic Gas should be expanded to allow for factors such as the cost of design uncertainties, possible effects on schedules and maintenance costs.*

31. *The prudent approach to the design of buoyancy controls and pipe bends is the use of a suitably high factor of safety. The Company should consider the use of a varying safety factor with reference to the reliability and detail of site information, and the local consequences of uplift or buoyancy.*

Design Modification During Construction

The selection and design of buoyancy control measures depends upon site conditions. Decisions will be made well ahead of construction on the measures to be used where buoyancy problems may occur. For example, Arctic Gas have already decided to use a continuous wire-reinforced concrete jacket for the twin 36-inch lines at river crossings.

Despite the additional subsurface investigations to be carried out along the route prior to detailed design, it is reasonable to expect that some buoyancy problem areas not identified at the design stage will be encountered during construction. Under the proposed construction schedule, such areas would have to be identified by field inspectors, and appropriate design changes implemented.

With the rapid pace of construction, it will be difficult to ensure that all potential areas of pipe buoyancy not identified during design are recognized, and the necessary design changes implemented. Because of the great demand for geotechnical inspectors on this project, they may not be sufficiently experienced to detect, under winter conditions, changes in site conditions significant enough to affect pipe buoyancy and pipe bend design.

32. *Because it is desirable to limit the possibilities of pipe uplift, the Company should examine, from the standpoint of buoyancy control, the difficulties associated with field checking and inspection. The Company should demonstrate to the satisfaction of the Agency how it intends to overcome these difficulties. There is a need, for example, to establish local guidelines to assist the inspectors in recognizing and evaluating, under winter conditions, site facts that are conducive to pipe uplift.*

Monitoring and Remedial Measures

Even with a proper design approach and effective field control, it is possible that areas with potential buoyancy problems will be overlooked during design and construction. Significant changes can also occur during operation; for example, erosion and slumping of the backfill mound, and the melting of permafrost south of the limit of refrigeration, could result in buoyancy problems. Because most problems are expected to arise during the initial years of operation, the pipeline companies propose to include in their monitoring program an inspection of all aspects related to buoyancy.

33. *The Company should study in detail the engineering and environmental problems that could result from an uplifted or floating pipe, the feasibility of various remedial measures, and the impact of these measures on the environment.*

Buoyancy of Pipe Following Abandonment

Both Arctic Gas and Foothills propose to leave the pipe in the ground following abandonment. They have suggested that those portions of the pipe that may become buoyant could be filled with water. This concept has not been studied in detail. In one sense, any buoyancy problems that might develop after abandonment have the greatest potential for adverse impact, because it is not yet decided who will be responsible for remedial actions. Without decisions and agreements in this area, problems may well go unattended.

34. *Before start-up of the pipeline, the Company should submit to the Agency a detailed plan on the problems and remedial measures for pipe flotation after abandonment.*

35. *The Agency and the Company should reach a formal agreement on who will be responsible for any necessary remedial actions after pipeline abandonment, and on how these actions will be funded.*