NEW DESIGN CONCEPTS FOR PIPELINES BURIED IN PERMAFROST

John G. Greenslade
Colt Engineering Corporation
E-mail: greenslade.john@colteng.com

Derick Nixon
Nixon Geotech
E-mail: derickn@cadvision.com

ABSTRACT
This paper outlines some of the recent design developments and construction support efforts of the authors and their colleagues that reduce the capital cost and enhance the design integrity and environmental performance of pipelines buried in permafrost.

These new design concepts can significantly reduce the expected cost of a major northern gas pipeline relative to historical conceptual costs.

Recent North Slope of Alaska oil developments have successfully utilized new design concepts for warm buried crossings of major rivers to achieve certain environmental and economic objectives. The fully buried oil pipeline from Normal Wells, NWT, originally designed as a cold pipeline, has successfully operated in recent years as an ambient temperature system. These developments widen the application and improve the potential cost advantage of buried oil pipelines over above grade pipelines in permafrost.

INTRODUCTION
The concept of burying pipelines in permafrost is not new. This paper identifies the major lessons learned from existing pipelines buried in permafrost, outlines a design approach to minimize the cost of a buried gas pipeline and introduces environmental design methods to achieve good environmental performance of the right-of-way (ROW) of a pipeline buried in permafrost. Thaw settlement and frost heave are critical design issues that are central to optimizing the design and obtaining good environmental performance of the ROW. Strain based design is necessary for most pipelines buried in permafrost. An overview is provided of thaw settlement, frost heave and strain based pipeline design.

DESIGN ISSUES AND LESSONS LEARNED FROM OIL PIPELINES
The well known Trans Alaska Pipeline (TAPS) has very successfully moved North Slope oil from Prudhoe Bay to Valdez since 1977, normally at about two million barrels per day. TAPS is generally thought of as an above grade line, however in fact virtually half its length is buried. TAPS is a 48-inch O.D. hot oil pipeline. It has created a thaw bulb over one hundred feet in radius around the pipe. Above a certain ice content, there is a volume reduction associated with the melting of frozen soil. It is common for permafrost to have an ice content as high as 50% or more in the top several feet. This gives rise to thaw strain, the reduction in volume of a mass of soil relative to its undisturbed volume, of 40% or more when the permafrost is thawed. In practical terms, the consequence of a pipeline melting ice rich permafrost is settling of the area beneath which thaw straining has occurred, hence the term thaw settlement.

Thaw settlement of ice rich permafrost creates profound pipeline design concerns with respect to both the mechanical integrity of the pipe and the environmental performance of the right-of-way. The solution selected for TAPS was to undertake an extensive geotechnical investigation ahead of construction to identify thaw susceptible areas. The pipe was buried wherever thaw stable soils were encountered and the familiar above grade design was adopted in ice rich, fine-grained soils where large thaw settlements would have occurred. Although it is generally recognized that the cost of an above grade pipeline is greater than its buried counterpart, above grade construction remains a very good design solution for warm pipelines in thaw susceptible soils.

The Norman Wells pipeline in Northern Canada took a very different but similarly successful approach to pipelining in permafrost. It was designed as a cold buried pipeline. To minimize the thaw settlement problem, the original design called for the oil to be refrigerated to near ground ambient temperature before it entered the pipeline. The Norman Wells pipeline originates in a region of warm, discontinuous permafrost and, like TAPS, runs generally southward to...
a significantly warmer region and ends in sporadic permafrost. The cold buried design concept introduces an additional design issue, frost heave. Frost heave is essentially the converse of thaw settlement. When a pipeline carrying oil at below 32°F traverses naturally unfrozen soil, a frost bulb is created around the pipe. The soils within the frost bulb expand as they freeze.

Notably, thaw settlement remains a design concern for the Norman Wells pipeline. As the oil moves downstream from the pipeline inlet, the influence of inlet temperature on the temperature of the oil diminishes. Its temperature is increasingly influenced by frictional heating and heat exchange between the contents of the pipe and its surroundings. At some point, the oil temperature rises above the freezing point of the soil. When oil above 32°F flows through permafrost, thaw settlement is a design issue. The design of the Norman Wells pipeline for frost heave and thaw settlement can be found in the literature (Nixon, Stuchly and Pick, 1984).

The recently constructed Badami pipeline, east of Prudhoe Bay on the North Slope of Alaska, introduced another design option; a warm buried pipeline in thaw susceptible soils. The Badami pipeline was built above grade except for the major river crossings, which were buried. This design pioneered the concept of placing an engineered soil layer beneath the pipe to limit the curvature of the pipe, hence the strain level, that results from thaw settlement within the thaw bulb. The authors of this paper were principals on the design team for the Badami pipeline.

The Norman Wells and Badami pipelines are both 12.75 inch O.D lines designed for about 35,000 barrels of oil per day. The design approaches taken on those pipelines are thought to afford improved project economics over the above grade option. Figure 1 (see attached) is a route map showing the locations of the buried crude oil pipelines in North America. The very different design solutions employed on these pipelines indicate that there is no universally applicable design solution for the fascinating challenge of designing an oil pipeline in a permafrost region.

The Alpine project has a buried crossing of the Colville River but the pipes were placed in a talik (naturally thawed zone) beneath the river, hence this crossing does not add to our knowledge of buried pipelines in permafrost. Limited use has been made on the North Slope of pipelines buried in gravel fill. This design concept is generally uneconomic and its application seems limited to small lines that do not significantly change the thermal regime of the soils beneath the gravel fill.

**DESIGN ISSUES FOR GAS PIPELINES**

Gas pipelines buried in discontinuous permafrost present most of the same design challenges already introduced in the discussion of oil pipelines. Unlike an oil pipeline, however, where increased hydraulic loss is an economic burden on the cold buried design alternative, the hydraulic performance of a gas pipeline is enhanced by reducing the product temperature. Unlike the elevated option, even in permafrost the minimum operating temperature of a buried pipeline is high enough that obtaining adequate steel toughness is not a large economic burden. These considerations make the cold buried option attractive for a gas pipeline in permafrost.

The only operating gas pipelines buried in permafrost in North America are small diameter pipelines. The Walakpa pipeline serves the community of Barrow, Alaska and the Ikhil pipeline serves the community of Inuvik, NWT. Both these pipelines are cold pipelines buried in regions of cold, continuous permafrost, hence neither frost heave nor thaw settlement are design issues.

The TAPS fuel gas pipeline transports fuel gas along the oil pipeline as far as Pump Station 4 to supply fuel gas to the pump stations on the north end of the oil pipeline. The fuel gas pipeline has experienced some operating performance difficulties, including uplift buckling where heat from the nearby oil pipeline and haul road have melted the permafrost. The resultant loss of vertical restraint in a number of ice rich areas, in combination with significant compressive axial thermal stress has caused the pipeline to spring out of the ground a number of times at various locations. None of these uplift buckles has resulted in mechanical failure of the pipe. Uplift buckling is a significant design concern for most pipelines buried in permafrost.

A cold buried pipeline in discontinuous permafrost presents a set of design challenges not encountered on an oil pipeline. Whereas the pressure drop in an oil pipeline expresses itself in the form of frictional heating, the pressure drop in a gas pipeline creates Joule-Thompson cooling. As a consequence, frost heave is a major design concern and how it is handled is a significant economic driver for a northern gas pipeline.

**OPTIMIZING THE DESIGN OF A NORTHERN GAS PIPELINE**

Large gas reserves are known to exist in the Arctic regions of North America. Considerable work has been done periodically over the past three decades on the design of various northern gas pipeline schemes intended to move large volumes of gas from the Canadian Arctic Islands, the North Slope and the Mackenzie River delta to the south.

Some feel that it is now practical to move large volumes (about 3 BCFD) of North Slope gas offshore across the Beaufort Sea to Canada then come onshore and generally follow the Mackenzie Valley south to Alberta. A similar sized alternative generally follows the TAPS pipeline to Fairbanks, then the Alcan Highway into Alberta. Smaller potential projects recently in the news are a possible Mackenzie valley pipeline to deliver gas from the Mackenzie river delta to Alberta and the Alaska LNG (ANG) proposal to deliver about 1 BCFD of North Slope gas to a proposed new liquefaction plant near either Valdez or Anchorage. These routes are shown in Figure 2 (see attached).

Historically, gas pipeline proposals generally adopted the design premise that in the permafrost region, the gas should be refrigerated at each compressor station to below the freezing point of the soil in order to avoid thaw settlement. Frost heave would be handled by adding wall thickness as required to achieve acceptable strain levels in the pipe. Conventional wisdom suggests that compressor stations be large and relatively widely spaced.

It is our contention that significant improvement in the economics of a northern gas pipeline can be achieved by adopting a design philosophy quite different from the one described above. We suggest a design approach that focuses on minimizing the tonnage of steel in the project. This may seem intuitive but big project organizational
structures tend to prevent that from happening. Pipe, construction and infrastructure costs are all closely tied to the tonnage of steel in the line pipe. The cost of the compressor stations on a major northern gas pipeline will be small relative to the installed cost of the pipe.

We think the following steps provide the key to optimizing a northern gas pipeline:

1. Organize for success. Allow adequate time in the project schedule for a small, highly qualified team to develop the conceptual design. Do most of the geotechnical fieldwork as part of conceptual, not detailed design.

2. Select the design pressure that minimizes the required tonnage of line pipe. Within reason, increasing the design pressure reduces the required line size, the hydraulic losses and the geotechnical loads but increases the hoop stress. The optimum pressure is likely to be between 2,000 and 3,000 psi.

3. Establish a "designer temperature profile" for the pipeline. Have the geotechnical design team establish a pipeline temperature profile that avoids having large geotechnical loads add wall thickness to the pipe. This produces the minimum wall thickness necessary for acceptable hoop stress levels with little or no additional wall thickness required to handle thermal stress and bending strain. With this design philosophy, the station spacing and station size are dependent upon the ambient ground temperature and surficial geology as well as conventional station design criteria.

4. Specify the optimum pipe. This likely means at least grade X-70. Whether higher grades are economic depends on project specifics. Specify the exact diameter and wall thickness that best fit the project. There are no economies to be realized on a large northern gas pipeline by using standard pipe size or wall thickness.

5. Accept the use of surprisingly many, unusually small compressor stations that are necessary to realize the designer temperature profile.

6. Simplify the compressor stations. Apply the "learnings" from recent operating experience from the Norman Wells pipeline to adopt a passive system where above freezing compressor station discharge temperatures are tolerated during warm weather and "cold is stored" during the cold winter months. It is expected that this strategy can be employed to eliminate refrigeration from all but the initiating station.

7. Install stand by compressor capacity only at the initiating station. Design the system for enough capacity to meet the daily minimum volumes with any but the initiating compressor station down.

8. Minimize the infrastructure. Build airstrips as required instead of roads. Hercules aircraft are readily available and have a payload capacity comparable to that of a semi-trailer highway truck.

9. Use ice roads and aircraft to support construction. Insulated ice pads can store materials and equipment over summer as required. Gravel is expensive in the north and earth works built from frozen gravel require considerable rework in a summer season before they can be used during summer months.

10. Utilize modern pipeline construction and inspection technology. This includes automatic welding and digital girth weld inspection records. Establish project specific weld acceptance criteria that minimize the project cost. This may mean more restrictive weld acceptance criteria than the maximums allowed by either API 1104 or CSA Z-662.

11. Choose aggressive strain limits. Use full-scale bend tests to validate the selected design strain limits. A lot of tons of steel depend on this key design parameter.

12. Commit to the frequent use of modern pipeline inspection technology. Monitor rigorously for corrosion and pipe curvature. Stop corrosion at the earliest opportunity. Use engineered critical assessment (ECA) analysis to establish safe operating strain levels (they may be higher than the design strain limits.) This is only feasible if 100% non-destructive examination (NDE) of girth welds has been done by a method such as automated UT that creates a reliable, permanent digital record of weld flaw size and location.

13. Adopt the ditch backfill design criteria developed for the cold buried Badami pipeline design (Greenslade and Nixon, 1998) and apply the lessons learned on the Norman Wells pipeline (MacInnes et al, 1990) to achieve good environmental performance of the right-of-way.

THAW SETTLEMENT

Where a warm pipe is buried in permafrost, differential settlement causes the pipe to bend. Where abrupt transitions occur between thaw stable and thaw susceptible soils, high pipe strain levels can occur. In general, these transitions are so numerous and their occurrence is so unpredictable that we do not subscribe to the design approach that has been espoused by others of specific design to account for these transitions. Instead, we advocate adopting regional designs based upon extreme thaw settlement predictions from geotechnical boreholes and a "worst case" settling length. If the maximum thaw settlement feature identified from the geotechnical field program is hypothetically placed within a thaw stable section, the system can be modeled and solved for the length of the thaw susceptible interval that produces the maximum pipe strain. See Figure 3. This design basis, in combination with an intensive pipe curvature-monitoring program during the early months of production, is our suggested method for balancing risk and cost. There is little likelihood that the most thaw susceptible section of the alignment will be drilled during the geotechnical field program. Conversely, however, there is little likelihood that large thaw settlement features will have critical lengths. This design approach involves some risk that geotechnical "repairs" (excavating a section of pipe to relieve the
strain then installing thaw stable material beneath the pipe) will be required during the first few months of operation. It is our view that the economic cost associated with this risk is far less than the cost of greatly increased geotechnical drilling or a more conservative design. This design approach requires a commitment to run pipe curvature surveys early in the operating life of the pipeline at times computed by the geotechnical and pipe stress teams to ensure that geotechnical repairs are made as required to prevent excessive pipe strain. From Figure 3, it can be seen that for the assumed design conditions, if the design thaw settlement occurs with a span length between 25 and 43 feet, a geotechnical repair would be required.

![Maximum Axial Pipe Strain](image)

**Figure 3**

**PIPE STRAIN VS THAW SETTLEMENT SPAN LENGTH**

Particularly where deep burial is required at river crossings and overburden loads on the pipe are large, it may be economic to over excavate and install an engineered layer of thaw stable material beneath the pipe. This is driven by two considerations. Local conditions may occur that would prevent the operator from effecting a geotechnical repair economically or with acceptably low environmental disturbance. High overburden loads (deep burial) in combination with unfavorable soil conditions may make it impractical to add sufficient wall thickness to realize adequate pipe section.

FROST HEAVE

For a gas pipeline, the Joule-Thompson cooling associated with the pressure drop between compressor stations will result in cooling. If the mean annual pipe temperature falls below 32°F, a frost bulb will advance into the soil beneath the pipe that may not thaw out each year, depending on the undisturbed ground temperature. For example, if gas enters the pipe at a temperature of 32°F or slightly above 32°F, then the line temperature will fall steadily to some temperature such as 24°F or colder, depending on the pressure drop and the length of pipeline between compressor stations. Freezing in fine-grained saturated soils results in the growth of ice lenses and upward movement of the pipe with time. As the pipeline passes from frozen (stable) ground to unfrozen (heaving) ground, differential soil displacement will produce bending strains in the pipe near the transitions.

Frost heave is a function of pipe temperature and soil type, and to a lesser extent on pipe diameter. New frost heave prediction methods, and better uplift resistance functions have been developed in recent years (Nixon, 1994). The dependency of frost heave on pressure can be predicted for use in a pipe structural model. The resistance to pipe uplift by the soil in the non-heaving (frozen) section can be estimated from published correlations (Nixon, 1998) and can be input to the analysis. This parameter is dependent on the overburden load on the pipe, the soil temperature and the local heave rate. The higher the uplift resistance, the greater the pipe strain near the thermal interfaces between frozen and unfrozen terrain.

A pipe structural model is used to predict the pipe strain resulting from large soil movements. By studying a range of below freezing pipe operating temperatures and a highly frost susceptible soil, it is possible to establish a minimum (coldest) mean annual pipe operating temperature that will avoid adding materially to the pipe wall thickness required by hoop stress considerations. Hence, by limiting the allowable minimum mean pipe temperature, it is possible to minimize the pipe wall thickness required to account for the soil loads associated with frost heave. In this way, the pipe operating temperature profile can be optimized to achieve a minimum cost for each station-to-station pipeline segment.

OPTIMIZING THE TEMPERATURE PROFILE OF A GAS PIPELINE

In general, the pipeline temperature profile should be kept as close to ambient ground temperature conditions as practical to minimize the impact on the pipe of geotechnical loads from frost heave and thaw settlement. In the discontinuous permafrost region, frequent randomly placed transitions between frozen and thawed ground occur, typically several times per kilometer (Nixon et al, 1991). It is not practical to design for each of these interfaces; the design should be robust and insensitive to varying thermal and geotechnical conditions. This means the pipe must be able to accommodate the differential soil movements caused by thawing and freezing beneath the pipeline.

Gas flowing in a pipeline loses pressure along its length. This can result in several degrees of Joule-Thompson (J-T) cooling between adjacent compressor stations. The pipeline normally loses heat to the surrounding soil, and the temperature in the flowing gas can fall below the surrounding ambient temperature, creating frost heave issues. Figure 4 shows in a simplistic way the dependence of the J-T parameter (degrees of cooling per unit of pressure drop) on the selected operating pressure for a typical gas composition. It is apparent that higher operating pressures result in less J-T cooling than conventional gas pipeline operating pressures. Operating in the normal 1,000 to 1,400 psi range is very likely not optimal for a gas pipeline in permafrost. Operation at higher pressure will result in lower J-T cooling and reduced mitigation requirements for frost heave effects.
It appears feasible to operate a gas or oil pipeline at temperatures in excess of 32°F, so that the mean operating temperature may be at or somewhat above the melting point. The Norman Wells pipeline provides an important case study in this regard. In 1993, the operator of this line obtained approval to operate the pipeline at a mean annual temperature of 32°F out of Norman Wells, increasing to as much as 50°F in the summer months. This has performed well in the intervening years (Nixon and Burgess, 1999) resulting in large operating cost savings. For a new pipeline, this design approach would significantly reduce both capital and operating costs.

The allowable discharge temperature (both mean and seasonal variations) is a function of two important factors, the mean ground temperature and the amount of excess ice in the soils beneath the pipe. The further north the pipeline, the lower the mean ground temperature. In cold permafrost, the mean annual operating temperature can exceed 32°F by a small amount without inducing significant thawing. The pipe can tolerate limited thaw settlement but it is necessary to ensure that environmental degradation from progressive thaw settlement in icy terrain does not occur. Further south, the mean annual pipe temperature can be about 32°F and relatively large seasonal variations are permissible. This flexibility in operating temperatures is important in reducing compressor station costs. It should be noted that the warmer the pipeline inlet temperature (compressor station discharge temperature) the warmer the outlet temperature (compressor station inlet temperature.) This helps reduce the frost heave mitigation requirement.

The design process involves selecting an operating pressure and an inlet temperature function that minimizes thaw settlement and frost heave mitigation requirements and therefore minimizes the pipeline cost. It is important to carry out geotechnical and pipe strain analysis before the process design and pipeline hydraulics studies in order to establish suitable limits for the operating temperature range. Traditionally, pipeline design projects have been structured differently, with the pipe operating conditions and hydraulics studies being established before the geotechnical and pipe strain analyses are carried out; this rarely leads to an optimal design.

**Figure 4**

TYPICAL CORRELATION FOR J-T COEFFICIENT

![J-T Coefficient Graph](chart)

---

**Figure 5**

HOOP STRESS LIMITS FOR 80 KSI YS PIPE

- **Typical Burst Strength**
- **SMYS = 80 ksi @ 0.5% Strain**
- **Hamburg-Org-Welt with γ = 17**
- **CSA Hoop Stress Limit = 0.7 SMYS**
- **ASME Hoop Stress Limit = 0.72 SMYS**

---

### STRAIN BASED LIMIT STATES DESIGN

Strain based design is necessary for pipelines buried in permafrost. The essence of strain based design is designing to pipe strain limits instead of stress limits. Where axial stress or bending strain contribute significantly to the combined stress on the pipe, as is the case for a pipeline buried in permafrost, the combined stress can safely exceed the yield strength of the steel in the pipe. Strain based design of buried pipelines is a recognized part of limit states design in the CSA pipeline code. Soil resistance can effectively limit the bending here the strain level of the pipe. Strain based pipeline design necessitates the establishment of a set of strain limits for various load combinations. Normally, different tensile and compressive strain limits are established for each of several design load combinations. Typically, strain based pipelines are designed for an assumed stress-strain curve. Once the pipe has been manufactured, stress-strain curves should be obtained for both the circumferential and longitudinal directions to validate the design strain limits and to establish operating strain limits.

Soil loads are not effective in limiting the response of the pipe to internal pressure. Never the less, limit states design can be used to reduce the wall thickness, hence the design factor on hoop stress. Although this is commonly done for offshore pipelines, we do not advocate this use of limit states design for pipelines buried in permafrost. We prefer to design to familiar stress limits for hoop stress. These design principles are illustrated in Figures 5 and 6.
Strain based pipeline design is a rational basis for the design of pipelines that are exposed to large thermal stress or bending strain. It should not be thought of as inherently more risky than stress based pipeline design. Often the hoop stress in a strain-based pipeline is below the stress level allowed by code, unlike most stress based pipeline designs. For pipelines with large thermal stress or bending strain, the implicit design factors on secondary loads for stress based design according to the CSA or ASME pipeline codes are large relative to the design factors on the primary loads, most notably internal pressure. This is both illogical and uneconomic. It creates a powerful argument for the adoption of limit states design with appropriate strain limits used in place of combined stress limits for those loading effects that produce pipe strain that is limited by soil resistance.

In establishing the strain limits for a pipeline subjected to large bending loads, the designer should think in terms of the mode and the consequence of failure. It is useful to discriminate between functional failure and loss of containment. Excessive compressive strain is likely to result in uplift buckling, wrinkling or buckling of the pipe, not loss of containment. This constitutes functional failure in the sense that the pipe would displace out of the ground or no longer be able to pass inspection tools. In the extreme, an unacceptable hydraulic restriction could occur. Functional failure necessitates either a geotechnical repair or a geotechnical and mechanical pipeline repair but is unlikely to result in loss of containment. Intervention can normally be scheduled for the next winter construction season, when overland travel is possible and adverse environmental impacts can be minimized. Tensile failure, on the other hand, is almost certain to result in loss of containment and require immediate intervention. Plastic collapse is a function of the diameter to wall thickness (D/t) ratio. For these reasons, separate, normally different design tensile and compressive strain limits should be specified.

Consideration of the consequence of failure supports the use of relatively aggressive compressive and relatively conservative tensile strain limits. Similar logic leads to adopting more aggressive tensile strain limits for gas pipelines in remote areas than for oil pipelines. Logically, pipelines buried in permafrost would be based upon probabilistic limit states design methods. Interestingly, for pipelines that operate at temperatures above the installation temperature, thermal stress serves to increase the compressive strain and diminish the tensile strain that occurs when the pipe is bent. The net effect is that thermal stress normally serves to increase the tolerable bending strain on a pipeline buried in permafrost.

The tensile strain limit, steel grade, allowable weld flaw size and weld toughness are intimately linked. Various design options are available to the designer and different schools of thought exist as to what constitutes best design practice. Design tensile strain limits are generally established for the worst case scenario of the largest acceptable weld flaw being located at the point of maximum tensile strain. In practice, that is not likely to be the case, hence a distinction should be made between the design tensile strain limit and the maximum allowable operating tensile strain limit. Achieving both an economic design and the safe operation of a strain-based pipeline requires an integrated approach to design, construction and operation. Aggressive design strain limits should be combined with NDE of all pipe fabrication and field construction welds that quantifies the size and position of weld flaws, and pipe curvature monitoring throughout.

---

**Figure 6**

![Graph showing typical strain limits for 80 ksi YS pipe](http://electrochemical.asmedigitalcollection.asme.org/IPC/proceedings-pdf/IPC2000/40245/V001T02A008/2507445/v001t02a008-ipc2000-118.pdf)

As previously discussed, geotechnical loads from thaw settlement and frost heave are critical design issues for pipelines buried in permafrost. The amount of thaw settlement and frost heave is dependent upon the thermal disturbance created by the pipeline and the nature of the soils within the thaw and frost bulb. To design a buried pipeline in permafrost, an accurate thermal model is required. One of the authors (Nixon, 1983) has developed a geothermal simulator that has been used extensively for that purpose on the Norman Wells, Badami and other pipelines. Methods can be taken from the literature to predict the thaw settlement and frost heave potential of various types of soil. Extensive geotechnical evaluation of the soils along the pipeline route is necessary in order to reliably predict the geotechnical loads on the pipe. Considerable experience and good engineering judgement are necessary to design an adequate, economic geotechnical field program upon which to base the design.

Differential soil displacement caused by thaw settlement and frost heave can easily amount to several feet of vertical movement over tens of feet of axial length, in which case bending, not internal pressure or combined stress, dominates the assessment of the mechanical integrity of the pipe. A large displacement, nonlinear pipe-soil interaction model such as PIPLIN is required to accurately model the pipe strains that result from the predicted soil displacement fields. To adequately model the pipe strain resulting from such large differential soil displacement, the stress-strain response of both the soil and the pipe material must be modeled not only in the elastic region but also in the plastic region, hence the requirement for a nonlinear simulator. The bending of the pipe is such that significant elongation of the pipe occurs, hence the requirement for a large displacement simulator that considers the cable tension effect on the resulting pipe strain.

Detailed nonlinear analysis is required for the of the pipe-soil system at bends. The design issues are wrinkling, plastic collapse and uplift buckling. The design challenges are particularly large for the case of a pipe surrounded by a thaw bulb. Bend radius restrictions, increased burial depth and the use of imported soils are amongst the available design solutions.
the life of the pipeline to monitor bending strain. Crack tip opening displacement (CTOD) testing of both the pipe body and welds is necessary to achieve a balanced design in terms of pipe body and weld toughness, and weld flaw acceptance criteria. CTOD testing of welds is required during the welding procedure development and qualification to ensure that both pipe fabrication and field welding procedures support the strain based design.

CODE ISSUES IN THE USA AND CANADA

The ASME pipeline codes provide no guidance for the design of pipelines buried in permafrost. Neither B31.4 nor B31.8 addresses how to handle bending stress on a buried pipeline, nor do they deal with limit states design. The designer is obliged to invoke the opting out provision of the code that requires the designer of pipelines involving "complex or combined stresses" to "apply more complete and rigorous analysis to special or unusual problems". Clearly, a pipeline buried in permafrost falls into this category. One approach that can be taken to resolve this difficulty is to reach agreement with the Owner and the Regulators to follow a pipeline code that does recognize strain based design of buried pipelines. The British, Dutch, Norwegian and Canadian codes are obvious candidates. Of these, only the Canadian code is significantly influenced by knowledge obtained from a major pipeline buried in permafrost, the previously mentioned Norman Wells pipeline. The European codes have an offshore focus and take a probabilistic approach to pipeline design. The Canadian code has more similarities to the American codes and was generally followed for the strain-based portions of the Badami designs.

The DOT regulations are quite specific in their references to the ASME pipeline codes and ASME or API procedures for the qualification of welding procedures. Although designers are wise to avoid the pitfalls of attempting to follow multiple codes, in this case, that seems to be the preferred strategy. The DOT regulations are quite prescriptive in the area of welding procedure qualification, however we feel that for a strain based pipeline it would be ill considered to ignore the more restrictive welding requirements of the CSA pipeline code. With respect to CTOD testing, however, we prefer the approach taken by the British Standards.

For Canadian pipelines, the designer has little choice but to follow the CSA pipeline code, Z-662. Although the current version of the code is arguably unnecessarily conservative, Z-662 is comprehensive in its treatment of strain based pipelines that are subjected to large bending loads. One of our main concerns with this code is the prescribed tensile strain limit of 0.5%, which we feel is unnecessarily conservative for a pipe that has no laminar defects or for a high quality weld. It is our opinion that equivalent mechanical integrity can be more economically achieved by specifying more restrictive weld acceptance criteria and adopting a higher tensile strain limit.

Our other main concern with the CSA pipeline code is its treatment in Appendix K of the maximum size of weld imperfections. With respect to both brittle fracture and plastic failure, the code seems to utilize imbedded assumptions regarding elastic behavior. We feel that this leads to excessive conservatism and drives design toward the uneconomic use of relatively low grades of steel, particularly at low temperature.

NEW ENVIRONMENTAL DESIGN METHODS

There are a number of peculiar design issues that must be addressed in order to obtain good environmental performance of a ROW in permafrost. They revolve around issues associated with thaw settlement, thermokarsting, erosion and disrupting water movement.

It is generally accepted that permafrost is fragile, and disturbing it can produce unacceptable consequences. When planning a buried northern pipeline, it is important to understand why that is so and what it means to pipeline construction. Unlike soils in temperate areas, permafrost is virtually impermeable. Other than what evaporates, all surface water is trapped in the active layer and on the surface. During spring runoff and after summer rains, large surface water flow, sometimes referred to as sheet flow, is normal. Where the surficial soils are silt and clay, they are generally ice rich and the tundra is normally capped with a thick, porous organic mat. Undisturbed, the system is stable and surprisingly resilient. Where the organic surface of the tundra is significantly damaged, normal surface water flow can create dramatic erosion on even the slightest slope. Increasing the depth of the active layer creates thaw settlement of ice rich soils. This traps surface water, which promotes thawing and increases thaw settlement. Wherever the organic veneer is breached, water erosion transports soil downslope. This causes more, often thaw unstable soil to thaw and the process continues, potentially creating massive, ugly erosion scarps. Early civil works and late season tundra travel in fragile permafrost areas have left ample evidence of this. Normal southern pipeline construction methods create unacceptable environmental disturbance in permafrost areas.

It is well established that construction on the tundra must be done from an ice pad. Typically, a minimum six inches thick ice pad, built from snow flooded with fresh water is required to protect the tundra from transport and construction equipment. Grading to obtain a smooth pipeline right-of-way is not tolerable. Leveling the ROW should be by means of temporary snow and ice fills. Grade cuts should be avoided if possible. They require extensive rehabilitation, usually involving covering the slope with gravel or wood chips. Both create permanent environmental disturbance. While protecting the tundra from construction damage is necessary, it is insufficient to obtain acceptable environmental performance of the ROW.

Ice rich permafrost can tolerate only a limited amount of heat input from the pipe without degrading the permafrost and creating surface settlements that would collect surface water. Where the terrain is essentially flat and the organic mat persists, this would lead to thermokarsting of the type that creates the beaded streams that are common on the North Slope of Alaska. Excess ice would melt within the thaw bulb. The water would rise to the surface and the surface of the tundra would settle. In many places, the potential settlement would be several feet. Where conditions are less favorable, erosion would result. The resulting erosion would need to be arrested and the damaged area restored but the cost would be substantial and the visual disturbance would likely be significant.

Various methods are available to control thaw settlement. For an ambient system as described for a gas pipeline with passive cooling or a pipeline in discontinuous permafrost, insulating the pipe may be necessary to limit the size of the thaw bulb. In extreme cases where vegetation is sparse and the land surface is covered by deep, very icy permafrost, such as in places near the Mackenzie River delta, the best
solution may be to construct above grade. Further south where vegetation is relatively lush, considerable general settlement of the ROW may be tolerable. On the North Slope, thaw susceptible soils often exist only as a very thin layer overlaying thaw stable sand and gravel. Most of the thaw bulb would be within thaw stable soils where little or no thaw settlement would occur. Experience indicates that near the coastline east of Prudhoe Bay, even a hot buried pipeline would produce maximum general ROW thaw settlement of relatively few feet. Under such geological conditions, some general thaw settlement of the ROW might be acceptable.

Another method of mitigating thaw settlement is to replace massive ice with thaw stable soil or to install a layer of imported thaw stable material of adequate thickness to compensate for the anticipated thaw settlement. In either case, to restore the area to a reasonably natural condition, the organic layer must be salvaged from the disturbed area and placed on top of the imported fill. It is suggested that the disturbed soil be seeded with an easily established but relatively non-persistent grass variety to stabilize the soil during the time it takes the native vegetation to become re-established. Wherever deep burial is required, such as at river crossings, this design approach is suggested. One additional design feature is necessary for riverbanks. To prevent erosion of the bank, a plug of suitable, coarse granular material should be placed from the bottom of the streambed to the top of the backfill to armor the bank against erosion. Figure 7 illustrates a typical backfill design of this type.

If only native spoil from the trenching operation were used for backfill, the trench of a pipeline in permafrost would be deficient in material. Even thaw stable materials are subject to thaw settlement of about 20% when they are excavated and replaced in the frozen state. Frozen soils experience a “bulking” when they are excavated and replaced. This is very pronounced when frozen soils are excavated by backhoe, less so with a wheel excavator. Inevitably, some snow and ice become mixed with the spoil pile. A berm is created over the trench during backfilling. When the material melts during the first couple of summers after construction, the resulting consolidation leaves rows of material on either side of the trench and a depression over the pipe. This creates an undesirable visual impact, and disturbs surface water movement so as to promote thermokarsting and erosion. It is not possible to recover all the material left alongside the trench. Our solution for this is to measure the volumetric deficiency within the trench, recognizing that some spoil is lost to erosion and some to voids in the tundra surface, and supplement the native spoil with good quality imported backfill material.

To measure the volumetric deficiency of the backfill, a design technique was developed during design of the Badami pipelines. A method was devised for predicting the overall thaw strain of the native backfill by means of a ditch settlement index (DSI) that is evaluated from geotechnical borehole samples. Greenslade and Nixon (1998) have reported this technique. The analysis indicated that a cold buried pipeline near the coast east of Prudhoe Bay would require about two feet of imported, select backfill beneath the native spoil. With this method, it is necessary to rework the backfill late in the summer season for at least the first and probably the second season as well, to move the surplus material along either side of the trench into the depression between the ditch walls. Because Badami was ultimately developed with the pipelines above grade except at the major river crossings, this approach has not been proven, although both the Walakpa and Iklik gas pipelines used the method, with apparently satisfactory results. This is illustrated in Figure 8.
Major northern rivers, although they may be frozen to bottom in winter, can have significant thawed zones (taliks) beneath them. These taliks can, and probably typically do, contain flowing groundwater. Crossing such rivers with a cold pipeline can have significant pipe stress (frost heave) and environmental consequences. Freezing the taliks can create upstream icings and could have undesirable consequences on fish habitat by reducing the supply of water to over-wintering holes downstream. An analysis of this phenomenon was undertaken as part of the cold buried pipeline designed (and permitted, but never built) for Badami. Greenslade and Nixon (1998) also reported this analysis, which requires a geothermal simulator with convective heat transfer capability.

CONCLUSIONS
It is technically feasible, environmentally acceptable and economically attractive to install buried pipelines in permafrost. For pipelines buried in permafrost, good engineering design includes good environmental design. Extensive geotechnical data, a reliable geothermal model and a large displacement nonlinear soil nonlinear pipe model are essential tools of the designer. Understanding and managing the modeled loads on the pipe from frost heave and thaw settlement are essential to optimizing the design. Limit state design is required. Hoop stress should be designed to stress limits; strain limits should be used instead of combined stress limits when considering the effect of combined loads that include thermal stress and bending strain.

REFERENCES


