Government-industry collaborative monitoring of a pipeline in permafrost – the Norman Wells Pipeline experience, Canada

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ABSTRACT
The Norman Wells pipeline, the first buried oil pipeline that traverses discontinuous permafrost in the Northwest Territories in Canada, has been the subject of terrain monitoring by both the operating company, Enbridge Pipelines (NW) Inc., and several government departments and agencies since 1984. The program includes monitoring the effects of pipeline construction and operations on the terrain, and collaborative research studying several unique soil-pipeline interaction issues. The numerous benefits of the program include data sharing between the participants, and ultimately the public. This program has assisted proponents and regulators in dealing with the project's environmental impacts and their mitigation, as well as with the design and environmental impact assessment of other proposed pipeline projects in permafrost terrain.

RÉSUMÉ
Depuis 1984, le gouvernement fédéral et Enbridge Pipelines (NW) Inc. entreprennent un programme de suivi du pergélisol et du terrain le long de l'oléoduc de Norman Wells, le premier oléoduc enfoui traversant la zone de pergélisol discontinu dans les Territoires du Nord-Ouest du Canada. Le programme collaboratif vise, entre autres, à déterminer les effets de la construction et l'exploitation de l'oléoduc et inclut une composante de recherche axée sur les interactions uniques entre les sols et la conduite. Les données acquises sont partagées entre les agences fédérales et la compagnie, et rendues accessibles au public – un de plusieurs bénéfices. Le programme d'observation et de recherche continue à aider les promoteurs et les organismes de réglementation à répondre aux impacts environnementaux. De plus il a contribué à la conception et l'évaluation environnementale d'autres projets de pipelines proposés pour la zone du pergélisol.

1 INTRODUCTION

The Norman Wells pipeline was constructed in the early 1980s to carry crude oil from near the Arctic Circle in northwestern Canada across the discontinuous permafrost zone to southern markets (Figure 1). It was the first fully buried oil pipeline operating in permafrost in Canada. Monitoring programs were required under conditions of the project's approval by the federal government's National Energy Board (NEB) and of the Environmental Agreement between the pipeline operator and the federal Department of Indian and Northern Affairs that was responsible for the management of the majority of lands along the route. A permafrost terrain research and monitoring program was developed collaboratively by the pipeline operator and several federal government agencies and implemented at the time of pipeline construction. The monitoring program focused primarily on geotechnical and geothermal performance of the right-of-way (ROW) at a series of instrumented sites both on level terrain and slopes, and the interactions with the ambient temperature pipeline. This program has now been in operation for over 25 years and during this time it has been responsive to changing regulatory requirements as well as dynamic environmental conditions. In addition, monitoring of off-ROW conditions along the pipeline route has provided valuable data regarding the impact of a changing climate on the permafrost.

This paper explores the nature, outputs and benefits (to the broader stakeholder community as well as the participating organizations) of the collaborative program. The value of the program in terms of the acquisition of data and generation of information and knowledge that can be utilized for future pipeline design and also environmental impact assessments is discussed. The paper will also discuss how the successful collaborative monitoring program can serve as a potential model for future northern pipeline projects.

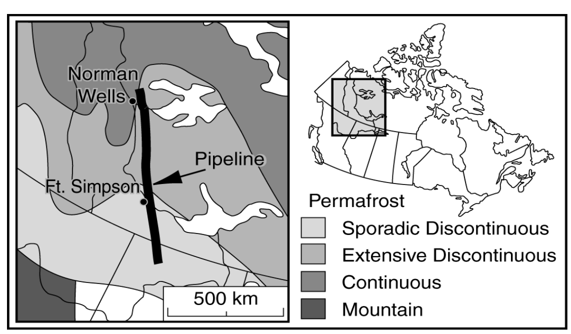

Figure 1. Location of Norman Wells Pipeline and permafrost zones in the region.

2 BACKGROUND

The Norman Wells to Zama pipe, operated by Enbridge Pipelines (NW) Inc. (Enbridge) is an 869 km small diameter (328 mm) ambient pipeline. The pipe is buried at nominally 1 m depth within a 25 m ROW over most of the route. Construction took place during the winters between 1983 and 1985 and operation began in spring 1985.

The route crosses unconsolidated Quaternary deposits of the Mackenzie Valley and Alberta Plateau and the discontinuous permafrost zone (Figure 1). Permafrost in the northern portion of the route is colder (-1 to -3°C), more extensive, and thicker (up to 50 m thick) compared to that in the southern end of the route where permafrost is sporadic, only a few meters thick and at temperatures close to 0°C (e.g. Burgess and Lawrence 2000; Smith et al. 2008b). The discontinuous distribution of permafrost means that there are numerous transitions from frozen to unfrozen terrain, which may be as frequent as 10/km over the southernmost 200 km of the route. Lacustrine sediments and tills dominate the northern portion of the route with tills and organic soils becoming dominant in the south (Burgess and Lawrence 2000). The frozen lacustrine sediments and organic terrain are often ice-rich and have high thaw strains that can have implications for infrastructure performance.

The permafrost and terrain conditions along the route necessitated the development of unique design features and mitigation measures to reduce terrain disturbance such as thaw settlement resulting from thermal effects of pipeline construction and operation. The design had to ensure pipeline integrity under potential conditions of frost heave, thaw settlement and slope instability.

Oil entering the line is chilled at Norman Wells with no chilling at the two other pump stations (located at KP336 and KP585). Oil was initially chilled to a constant temperature of about -1°C throughout the year before entering the pipeline, to approximate the average annual ground temperature (of -2 to -3°C) in the Norman Wells area and hence to reduce the heat input into the ground. In 1993 a seasonal chilling cycle, with oil temperature entering the line rising above 0°C in the summer and falling below 0°C in the winter while maintaining an average annual temperature between 0°C and -1°C, was introduced. The pipeline then adjusts to the average ambient ground temperatures along the length of the route, with the exception of a 30-40 km section after each of the two downstream pump stations due to the 1-2°C increase in oil temperature during the pumping process.

The ambient nature of the pipeline distinguishes it from other oil pipelines in permafrost terrain such as the Trans-Alaska pipeline, which operates at temperatures of 38 to 63°C. The ambient thermal design minimizes the transfer of heat from the pipe to the ground. Clearing of the ROW with thinning or removal of the organic layer through grading during construction, however, results in warming of the ground and thawing of permafrost beneath the ROW, which had to be considered in the design. Construction along existing cutlines helped to reduce some of the environmental disturbance and improve engineering performance by aligning the pipeline through terrain that had already experienced some permafrost thawing (Oswell and Skibinsky 2006).

Other factors to be considered in design were the numerous slopes that were underlain by warm, thaw sensitive permafrost. A layer of wood chips was used to insulate 56 thaw sensitive slopes to retard thaw. Hand clearing and reducing ROW width on thaw sensitive slopes were additional mitigation approaches. Further details on engineering and design considerations and mitigation measures employed are found in MacInnes et al. (1989); AGRA and Nixon (1999); Naviq and AMEC (2007).

3 PERMAFROST TERRAIN RESEARCH AND MONITORING PROGRAM

The Geological Survey of Canada (GSC) of the Department of Natural Resources Canada (NRCan, formerly Energy Mines and Resources Canada) and the Department of Indian and Northern Affairs Canada (INAC) developed, in 1983, a cooperative permafrost and terrain research and monitoring (PTRM) program with the pipeline operator Enbridge Pipelines (NW) Inc. (formerly Interprovincial pipeline (NW) Ltd.). This program was implemented under the Environmental Agreement signed between the pipeline operator and INAC to improve evaluation and mitigation of impacts on the Norman Wells pipeline and future projects in permafrost terrain (MacInnes et al. 1990). Sites were selected and instrumented, shortly after ROW clearing and prior to commencement of pipeline operation, thus providing a baseline against which to gauge project related changes.

The principal objectives of the PTRM program were (MacInnes et al. 1990): (i) to determine and quantify impacts on permafrost and terrain; (ii) to evaluate recovery processes and effectiveness of mitigation measures; (iii) to compare actual and predicted impacts; (iv) to assess the adequacy of the regional environmental framework; (vi) to recommend improved environmental practices. The monitoring was initially planned for 5 to 10 years or until conditions stabilized. Although INAC's involvement in the field investigations greatly diminished after the mid-late 1990s, the GSC has continued the collaborative PTRM with the operator, maintaining monitoring sites, conducting research and establishing new field sites to address emerging issues.

The primary objective of the PTRM was to monitor permafrost, terrain and terrain stability and effectiveness of mitigation approaches along the ROW through a series of instrumented sites with a focus on borehole thermal instrumentation. A second major component was concerned with the evaluation of terrain performance along the entire ROW by periodic observation through aerial as well as ground surveys of, for example, revegetation, drainage and erosion, slopes, and ditchline settlement. GSC was heavily involved in both the design of the instrumented sites and engaged in related research associated with these two components. Other PTRM activities included two additional projects initiated in 1986: a National Research Council Canada project concerned with evaluation of the performance of wood chip insulation on thaw sensitive slopes, and an Agriculture Canada project focusing on the shallow (to depths of 1.5 m) soil thermal regime. These two projects continued until the early and mid-1990s respectively.

The PTRM instrumented site project consisted initially of 13 instrumented sites spread along the entire route. The GSC took the lead in the design, selection and thermal instrumentation for the monitoring sites, in consultation with the pipeline operator and their engineering consultants. Monitoring sites were selected to be representative of the various terrain types and permafrost conditions within the corridor, and of the construction and mitigation techniques employed. Sites included a wood chip insulated slope, thaw sensitive mineral and organic terrain, and frozen-unfrozen transitions. Each site consisted of one to three thermal fences, cross sections instrumented with temperature cables, for a total of 23 thermal fences. Each thermal fence generally consisted of two 5 m ground temperature cables within 3 m of the pipe, and two 20 m cables one of which was located on the ROW (4-10 m from pipe) and the other off-ROW (Figure 2). Thermistors were also placed on the pipe to measure pipe temperature. Monthly measurements and later high frequency measurements with data loggers, allowed characterization of the ground thermal regime and its evolution through time both on and off-ROW. A detailed description of the instrumented sites and the rationale for site selection can be found in Pilon et al. (1989) and

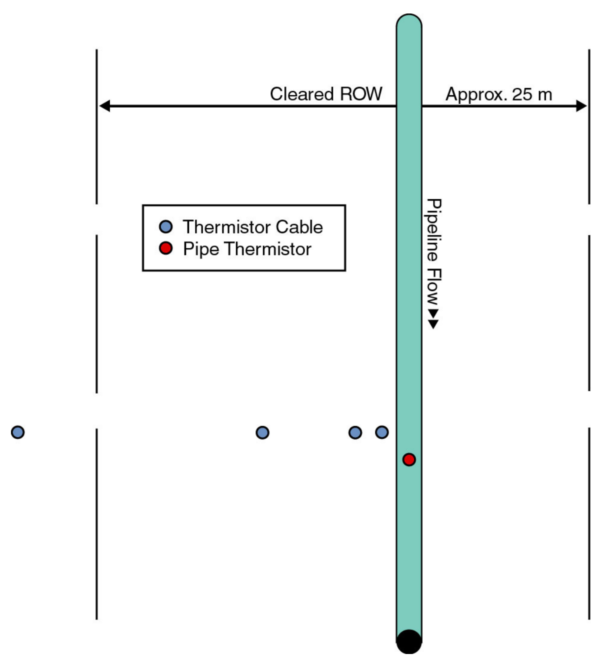

Figure 2. Layout of typical thermal fence with instrumentation to monitor pipe and ground temperature. Note: not to scale.

Smith et al. (2008b). Observations including those acquired through level surveys were used to document changes in the ground surface and pipe elevation over time. Geophysical surveys, such as ground penetrating radar and EM (electromagnetic), were also selectively conducted to increase knowledge of subsurface conditions.

The PTRM was distinct but complementary to the Enbridge pipeline and ROW integrity monitoring programs required by the terms and conditions of the NEB's certificate. Enbridge's program consisted of numerous activities including (Doblanko, et al. 2002)

- aerial line patrols
- in-line inspection tool monitoring
- instrumentation monitoring
- ROW brushing
- bathymetric surveys of water crossings
- ROW repairs (erosion control, replacing wood chip retaining cribs, reseeding, mitigating ditch line settlement)

The Enbridge monitoring first and foremost focused on two aspects: pipeline integrity and environmental stability. The installation of instrumentation was primarily directed to slopes, in contrast to the PTRM monitoring that initially and primarily focused on overland terrain response and related pipe-soil interaction. Enbridge's annual use of an in-line inspection tool, beginning in 1989, to monitor geometric changes in the first 336 km of pipeline provided valuable information on the changes in pipeline strains.

Both the operator and the government have the same broad goals of identifying impacts, improving mitigation, and reducing environmental impacts. Observations from both monitoring programs and sharing of these data between parties contribute to the annual performance evaluation required by the NEB and the Environmental Agreement and enhance the ability to address this goal. GSC and INAC participation in the annual geotechnical meetings with Enbridge and NEB has further ensured that observations and results from both PTRM and Enbridge monitoring are utilized in the development and updating of environmental management and monitoring plans/programs, and in the performance evaluation.

The PTRM and Enbridge integrity monitoring programs were flexible and were adapted or enhanced over time through the collaborative instrumentation of new field sites to adjust to dynamic environmental conditions and address emerging issues. These issues included hot spots on wood chip slopes, thaw beneath wood chip insulated slopes, changes to pipeline thermal operating conditions, forest fires, pipe deformation and creep of warm permafrost slopes.

4 KEY RESULTS/ACHIEVEMENTS

Over the past 25 years the PTRM program has generated key information that has improved our understanding of the interaction between pipelines and permafrost terrain, informed environmental management decisions for the Norman Wells pipeline and provided a

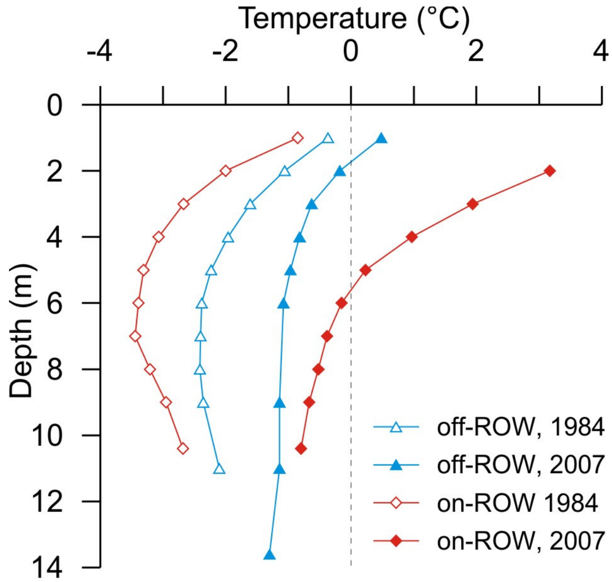

Figure 3. September ground temperature profiles on-ROW (5 m from pipe) and off-ROW (5.7 m from ROW edge) at site 84-1 (KP0.2) in 1984 (one year prior to start of operation) and 2007.

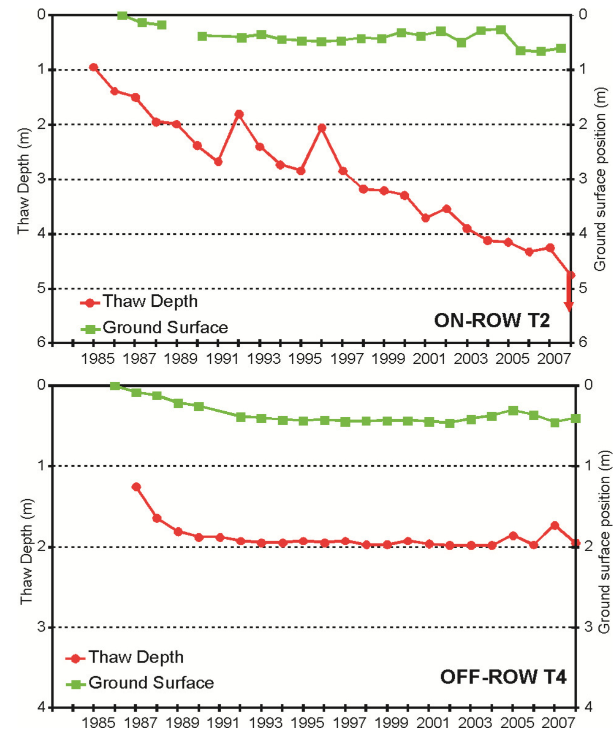

Figure 4. Thaw depth and ground surface position on-ROW (T2, 2 m from pipe) and off-ROW (T4, 5.7 m from ROW edge) at site 84-1 (KP0.2). The arrow indicates thaw is greater than the value shown.

wealth of data that has been utilized in the preliminary design and environmental assessment of the proposed Mackenzie Gas Project (Imperial Oil Resources Ltd. 2004). Numerous reports and scientific papers have been published and important databases have been released (see for e.g. Naviq and AMEC 2007; Smith et al. 2008b for bibliographies). A few highlights of the results and information generated by the program are presented below.

4.1 Long term thermal monitoring

One major achievement of the program was the establishment of a long term thermal monitoring program that has generated a record of ground temperatures beneath the ROW and the adjacent undisturbed terrain from construction through the entire operating period. Figure 3 presents data showing the changes in ROW fall ground temperature profiles over more than 20 years at one of the sites. These observations were essential for determining maximum annual thaw depths and for a comparison between the change in thaw depths on-ROW and that at control sites off-ROW (Figure 4). Comparison of observed values to predicted values allows an assessment of whether thaw depths remained within design values. This comparison also facilitated an assessment of the effectiveness of mitigation techniques such as wood chip insulation to reduce the rate of thaw penetration on slopes and whether further action or mitigation was required. Data from the off-ROW control sites was essential for determining how much of the increase in thaw depth may be directly attributed to the effects of the pipeline construction and operation.

The acquisition of pipe temperature data was essential for understanding the thermal influence that the pipe may have on the thermal regime of the surrounding soil and vice versa. These data were also valuable in examining the impact of changes in the pipe inlet thermal regime that became effective in 1993.

The 25-year long record of ground temperatures in the undisturbed terrain off-ROW is one of the longest permafrost monitoring records in Canada. These long term records facilitate the detection of the climate signal in permafrost. Analysis of these data indicates that permafrost is warming in the region, which is consistent with recent increases in air temperature (e.g Smith et al. 2005; Smith et al. 2010). This ongoing program provides a significant regional contribution to the Northwest Territories (NWT) Cumulative Impact Monitoring Program (CIMP) which was developed to meet requirements of land claims agreements and of the federal Mackenzie Valley Resource Management Act. The PTRM information has led to a better understanding of the regional environmental framework, of the impacts of climate change on permafrost environments (both through long term observations and modeling exercises (Burgess et al. 2000a; Smith and Riseborough 2010), and also of the overall effects that the environment may have on the pipeline performance.

4.2 Surface settlement

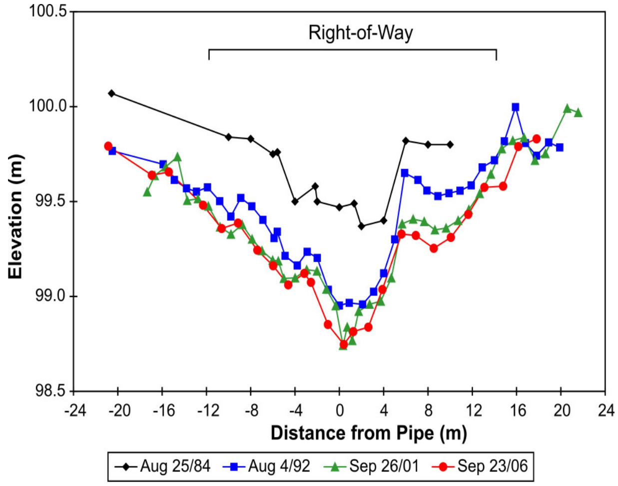

Figure 5. Ground surface elevation (relative to local datum) for selected dates across the ROW in organic terrain at site 84-5B (KP783). The first survey was conducted in first summer following pipe installation but pre-operation.

Increased thaw of ice-rich soils can lead to significant settlement of the ground surface, affecting drainage, ponding and erosion. Surface settlement may also be used as an indicator of possible pipe settlement (Burgess and Harry 1990). The ground surface position at each temperature cable (which is anchored in permafrost) has been recorded in the fall (time of maximum thaw) in order to determine cumulative ground surface movements that may be occurring in response to changes in thaw depth (Figure 4). Periodic level surveys have also been carried out across the ROW at many thermal fences. These observations have been used to better understand the geomorphic response of the terrain to the construction and operation of the pipeline.

The results of these studies (Burgess and Lawrence 1997; Burgess and Smith 2003; Smith et al. 2008a, b) have shown that greater settlement has generally occurred in the trench area compared to the rest of the ROW. Figure 5 shows the changes in the ground surface profile across the ROW with time at a permafrost site (KP783) in organic terrain near the NWT-Alberta border. Settlement was greater in the first few years following construction, with more than 50 cm occurring in the trench area at most of the study sites and up to more than 100 cm at some sites; ponding of water in the subsided trench frequently occurred in fine grained mineral and organic terrain. In some cases the initial pronounced settlement was likely due to the use of ice-rich or snow-contaminated backfill during winter construction. However, in many areas, it was likely due to the thaw consolidation of frozen blocky backfill (Burgess and Harry 1990). Considerable trench settlement was also observed in organic terrain, particularly immediately downstream from the southernmost pump station and where there are transitions from unfrozen fen to elevated frozen peat plateau. In this situation considerable collapse of the peat and widening and settlement of the trench have been observed (Burgess and Tarnocai 1997; Smith et al. 2008a). Settlement is still continuing but at a reduced rate.

The monitoring of surface settlement therefore was valuable for determining the effectiveness of techniques for backfilling the trench and planning further remedial measures. The observations were also used to calculate thaw strains for comparison with those determined for design and to evaluate predictions of thaw settlement.

4.3 Annual Meetings

While not a formal requirement of the NEB conditions nor of the INAC Environmental Agreement, Norman Wells pipeline annual geotechnical meetings have been held since the start of pipeline installation in 1984. The meetings focus on sharing and analysis of information on the performance of the pipeline, ROW and adjacent terrain, and discussion of mitigation approaches and monitoring plans, or remediation plans as necessary. The meetings are attended by representatives from Enbridge and their consultants, the NEB, INAC, NRCan, and since the late 1990s by the applicable land and water boards (such as the Mackenzie Valley Environmental Impact Review Board and the Mackenzie Valley Land and Water Board). These meetings do not constitute a formal third party or independent review by an oversight body. However, they are an important opportunity for information exchange, discussing refinements to the existing collaborative projects or development of new ones, and updating the various stakeholders on recent developments. As such, they have been an integral and important component of the environmental management, monitoring and follow-up programs, and have resulted in greater integration and collaboration both between federal departments as well as between these agencies and the NEB.

4.4 Other achievements

The PTRM program has been flexible enough to respond to emerging issues, which has led to additional field site establishment in collaboration with Enbridge. The change in 1993 from constant chilling of oil throughout the year at the pipe inlet to a seasonal chilling cycle resulted in establishment of a field site at KP2 to monitor the seasonal and cumulative pipe movements in response to the change in pipeline inlet temperature regime. This site, at a soil textural interface, was selected since the pipe temperatures would have been fairly constant year round (until 1993) because of its proximity to the inlet. The introduction of the seasonal oil temperature cycle would thus likely induce a greater range of seasonal heave/settlement than previously experienced, and additional thermal stresses in the pipeline which could lead to pipe strain or jacking. The initial surveys of pipe elevation at KP2 post 1993 indicated that there were seasonal pipe movements (20 cm) as well as a net downward movement of the pipe (Burgess et al. 1998 Nixon and Burgess 1999). The surveys have continued through to 2009 and the downward movement of the pipe still continues (Smith and Burgess, 2010 this volume). These pipe elevation and curvature surveys provided a field validation of the Enbridge pipe in-line integrity tool inspection data. The results can be combined with those of the more detailed integrity tool inspections done by Enbridge to determine if there are any pipeline integrity issues of concern.

Pipe uplift and deformation at KP5 following the 1993 introduction of the seasonal chilling cycle resulted in the pipe being exposed above the ground surface in 1997 and led to a collaborative field study to assess pipe movements and pipe strain. The study also evaluated the effectiveness of remedial action, which included placement of a gravel berm over the exposed pipe. Surveys of pipe elevation allowed assessment of the shape of the curvature and determination of the magnitudes of seasonal movements and an assessment of pipe strain (Nixon and Burgess 1999). Following remediation the magnitude of seasonal movements has decreased and there has been a net settlement of the pipe over time (Burgess et al. 2000b; Smith and Burgess 2010). The results show that the remedial action was effective at curtailing and reversing the direction of pipe movement and reducing strain (Doblanko et al. 2002).

Slow gradual downslope movements (creep) were found to result in pipe wrinkles at several slopes in the north-central portion of the route. Enbridge has installed slope movement monitoring equipment at six slopes and one off-ROW site. The recognition of the importance of creep led to collaborative instrumentation of slopes using slope inclinometers and thermistor cables to better understand the processes in these warm permafrost environments. Collaborative field sites were established at three locations, KP313 in 2001, KP195 in 2006 and the most recent at KP311 in 2010. At two of the sites in-place inclinometers connected to automatic data loggers have also been installed and it is hoped that the continuously recorded data will provide insights into the seasonality and long term rate of the movements.

5 KEY BENFITS OF COLLABORATIVE MONITORING

The benefits of the collaborative monitoring program are numerous. One of the most important was cost sharing during the establishment of the PTRM program. The pipeline operator's collaboration at the outset was substantial, covering the costs of drilling for all boreholes instrumented by the government in 1984 and 1985. The collaboration and in-kind support has continued as new field sites have been established. This has included sharing drilling rig mobilization-demobilization costs, accommodation support, data collection and helicopter support for site access or equipment transport. The most recent examples involved GSC's 2006 collaboration with Enbridge in the instrumentation of a slope at KP195 with ground temperature cables and inclinometers, and the 2010 installation by Enbridge of in-place inclinometers provided by GSC at KP311. Logistics were also shared amongst several government departments who were involved in the earlier years of the collaborative program, such as National Research Council and Agriculture and Agri-Food Canada, as well as NRCan and INAC. In these first several years, near monthly PTRM site visits for manual data collection, were made possible due to the support and involvement of locally-based INAC staff working from Norman Wells and Fort Simpson.

The Norman Wells pipeline research and monitoring program has been flexible, adjusting to the dynamic environmental conditions and emerging issues such as changes in pipeline thermal operating conditions, pipe strains, and creep as discussed above. These adjustments have involved, for example the addition of new sites or new parameters for monitoring, new instrumentation, changes to data collection frequency and reporting frequency, and implementation of new mitigation measures. Advances in data acquisition techniques resulted in automatic data loggers being installed on temperature cables at most sites. This reduced the need for multiple site visits each year while providing high frequency data collection which greatly enhanced the data analysis and research.

Both industry and government programs have adapted. This experience with the Norman Wells pipeline is one model for monitoring and follow-up programs, with monitoring requirements updated and revised based on data and observations acquired, regularly reported, and collaboratively reviewed.

The benefits of this collaborative approach have included ensuring that project related baseline and performance data were shared and analyzed, and results published. Key outputs include a monograph of pipeline geotechnical design and performance (Agra Earth & Environmental, 1999) and its subsequent update (Naviq and AMEC, 2007). In addition key databases (thermal, borehole geotechnical, ditch logs), case histories and synthesis products (e.g. Smith et al. 2004, 2008b) along with numerous reports and papers have been produced, some of which have been referred to here. A bibliography of most publications relevant to the Norman Wells pipeline project was compiled and the latest version published in Naviq and AMEC (2007). A key goal of the collaborative program was achieved, which was to document lessons learned for improvements to the Norman Wells and to future projects. The Norman Wells pipeline geoscience/geotechnical data have been made publicly available for use by proponents of future projects as well as governments and regulators, to assist in project design, environmental impact assessment and decision-making.

In addition, the long-term monitoring program has contributed to an improved understanding of the regional environmental framework and of the regional variations in permafrost response to climate change. The program has facilitated investigations of other factors affecting the permafrost environment including changing vegetation conditions and fire. The information and knowledge generated through the ongoing PTRM program constitute an important baseline for the NWT CIMP and support improved assessments of cumulative impacts in the region.

By being actively involved in terrain monitoring on the Norman Wells project and having access to industry's data, government has been able to conduct independent analysis and interpretation of effects and their verification against predicted impacts. This has perhaps represented an unparalleled level of technical study and appraisal, yet has provided an unprecedented level of data and knowledge accessible in the public domain. As well, those involved in Norman Wells pipeline geotechnical and environmental monitoring and research, whether as a formal condition of NEB or land use permits or Environmental Agreements, or informal collaborations, have met annually since 1984 for geotechnical review and information sharing meetings. There has been great continuity in both government and industry technical participants over more than 20 years, and associated capacity building in both communities.

6 CONCLUSIONS

A unique collaborative approach has led to a successful pipeline and terrain research and monitoring program for the Norman Wells pipeline. The PTRM program has generated an invaluable long term data record that has been used to better understand the impacts of pipeline construction and operation on the permafrost environment. The information generated by the PTRM has enhanced the effectiveness of the environmental management program.

The benefits of the collaborative approach are several and include cost and data sharing, collaborative field programs, and the ability to respond to emerging issues. The availability of industry's data to government for independent study and appraisal also led to unprecedented public availability of data and knowledge sharing. These benefits play a large part in ensuring reliable pipeline operation while reducing environmental effects. Corporate transparency may also be a collateral benefit.

The public availability of the data and research results generated by the PTRM program can be used, and have been used, in the design and regulatory processes of future pipeline projects, such as the Mackenzie Gas Project. This collaborative monitoring program may serve as one model for monitoring and follow-up programs for future development projects.

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