



PAPER AND REAL PIPELINES OF THE CANADIAN ARCTIC

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ABSTRACT

Following the 1968 discovery of oil in Prudhoe Bay, Alaska, hydrocarbon exploration in northern Canada generated widespread interest in pipelines southward from the Canadian arctic. Routes extended across the Yukon, Mackenzie Valley, the Arctic Islands, and down the west and east coasts of Hudson Bay. Geotechnical issues associated with northern development led to greater understanding of permafrost engineering and the impact of linear development on permafrost. During the 1970s several large pipeline projects were initiated and eventually abandoned, including Beaufort Oil Pipeline project, Canadian Arctic Gas Study Limited, Foothills Pipelines (South Yukon) Ltd. with the Dempster Lateral, and Polar Gas (east and west). A significant amount of research on these projects was conducted at the University of Alberta and by the Geological Survey of Canada.

This paper presents an overview of these early developments, including the significant increase in knowledge of permafrost engineering, pipeline-frozen soil interaction, slope stability in permafrost and other aspects. Full scale pipeline testing in Inuvik, NT, Norman Wells, NT, Quill Creek Yukon, and Calgary are discussed as is a summary of ditching trials in the high Arctic that tested trenching principles that are still applicable today.

RÉSUMÉ

À la suite de la découverte de pétrole en 1968 à Prudhoe Bay, en Alaska, l'exploration d'hydrocarbures dans le nord du Canada a suscité un intérêt généralisé pour les pipelines au sud de l'Arctique canadien. Les routes traversaient le Yukon, la vallée du Mackenzie, les îles de l'Arctique et le long des côtes ouest et est de la baie d'Hudson. Les problèmes géotechniques associés au développement nordique ont mené à une meilleure compréhension de l'ingénierie du pergélisol et de l'impact du développement linéaire sur le pergélisol. Au cours des années 1970, plusieurs grands projets d'oléoducs ont été lancés et finalement abandonnés, notamment le projet d'oléoduc Beaufort, l'Étude canadienne sur le gaz arctique, Foothills Pipelines (South Yukon) Ltd. avec le latéral Dempster et Polar Gas (est et ouest). Une quantité importante de recherches sur ces projets a été menée à l'Université de l'Alberta et par la Commission géologique du Canada.

Cet article présente un aperçu de ces premiers développements, y compris l'augmentation significative des connaissances sur l'ingénierie du pergélisol, l'interaction entre les pipelines et le sol gelé, la stabilité des pentes dans le pergélisol et d'autres aspects. Les essais de pipelines à grande échelle à Inuvik, NT, Norman Wells, NT, Quill Creek Yukon et Calgary sont discutés, tout comme un résumé des essais de fossés dans l'Extrême-Arctique qui ont testé les principes de creusement de tranchées qui sont encore applicables aujourd'hui.

1 INTRODUCTION

In the past five decades the development of northern hydrocarbons and their transport to southern markets has led to the planning and design of numerous northern pipelines. Yet despite the abundant resources available for development only three pipelines were

built from the time of the Second World War. This paper provides a summary of the proposed and constructed pipelines in northern Canada and lists some of the important advancements made in permafrost engineering as a result of these projects.

Current estimates for the entire global Arctic are reported to be a recoverable volume of 8 million cubic

meters (50 million barrels) of oil equivalent, 7 billion cubic meters (44 billion barrels) of natural gas liquids and approximately 47.2 billion cubic meters of natural gas (Ernst and Young, 2013). Figure 1 is a summary map of the large Arctic basins and the primary northern Canadian onshore deposits. This map shows that hydrocarbon-rich sedimentary bedrock extends in a wide arc from the Alaskan and Canadian Beaufort Sea over the Canadian Arctic Archipelago to Scandinavia and Russia. Oil and gas deposits are also present at sites along the Mackenzie River valley, particularly in the Norman Wells to Tulita area and in the Eagle Plains basin in the northern Yukon.

2 HYDROCARBON DISCOVERIES IN NORTHERN CANADA

Oil seeps along the banks of the Mackenzie River in the vicinity of Norman Wells were documented by Europeans as early as the late 1700s. Formal exploration and drilling followed the First World War. Imperial Oil Canada discovered oil near Norman Wells in 1920.

Hydrocarbon discoveries in arctic Canada occurred almost simultaneously in the high arctic islands (Sverdrup Basin) and in the mainland Mackenzie Delta area and adjoining offshore Beaufort Sea area (Mackenzie-Beaufort basin). Additional petroleum resources have been discovered in the Eagle Plain basin of northern Yukon Territory.

The hydrocarbon discoveries in the Mackenzie Delta and Canadian Beaufort Sea regions began with

the oil discovery in 1969 by Imperial Oil Limited at Atkinson Point on the Tuktoyaktuk Peninsula. This was followed by the major gas field discovery at the Parsons Lake site on the Mackenzie Delta. In the offshore Beaufort Sea, a large gas field was discovered in 1971 at the offshore Imperial Oil Taglu well. By 1995, total discovered petroleum resources were 360.2 billion cubic meters of gas and 223 million cubic meters (1380.5 million barrels) of oil in the Cretaceous and Tertiary-sandstone and siltstone reservoirs in the Mackenzie Delta and Beaufort Sea in the Mackenzie-Beaufort basin. Within several years, important onshore discoveries were made by Imperial Oil and Shell Canada and Gulf Oil Canada on Richards Island, Niglintgak Island and Parsons Hills.

Petroleum discoveries also occurred in the high Canadian Arctic islands in the late 1960s and early 1970s within the Sverdrup Basin and in the underlying Franklinian Miogeosynclinal shelf succession. The Panarctic Drake Point N-67 well at the northern tip of Melville Island drilled in 1969 was the first discovery well, followed by the 1974 Panarctic Bent Horn N-72 oil discovery on Cameron Island. The Drake Point well was Canada's largest gas field at that time. Oil from the Bent Horn field was transported by tanker to the Pointe aux Trembles refinery in Montreal, and, as of 1993, 321,469 cubic meters of oil had been produced (Morrell et al., 1995). By 1995, total discovered gas and oil resources were 406 billion cubic meters of gas and 66 million cubic meters of oil (Morrell et al., 1995).



Figure 1. Map of North American arctic showing known deposits of exploitable hydrocarbons (Adapted from Ernst and Young (2013) and Morrell et al. (1995)).

3 CANADIAN PERMAFROST PIPELINE ENGINEERING

The discovery of oil and gas reserves in the Canadian arctic initiated a two decade long period of research and engineering advancement to support pipelines in permafrost. One early example of this was a presentation by T.A. Harwood at the 3rd Canadian Permafrost Conference, held in Calgary in 1969. In that paper, he identified a number of technical challenges facing a warm-oil pipeline traversing the continuous and discontinuous permafrost from the Mackenzie Delta to Edmonton. He also identified a number of potential solutions, including laying the oil pipeline on the bottom of the Mackenzie River so that it avoided the permafrost.

Canadian permafrost science and engineering in the 1960s was of worldwide reputation with the likes of Roger Brown, Hank Johnson, John Pihlainen, Lorne Gold and Ross Mackay. However, these experts were either at universities or with the National Research Council and not employed by engineering companies.

Addressing a need for permafrost engineering consulting, a number of engineering companies contributed towards the design of northern pipelines. These companies included R.M. Hardy Associates Ltd (now Wood Group Plc), Elmer Brooker & Associates Ltd. (now TetraTech Inc.), Klohn Leonoff Ltd. (now Klohn Crippen Berger Ltd), and others. In addition, consortiums were formed to provide comprehensive pipeline consulting from single organizations. One project-specific consortium was Northern Engineering Services Company Limited (NESCL), formed to support the largest Canadian natural gas pipeline study, Canadian Arctic Gas Study Limited (CAGSL). This consortium included R.M Hardy Associates Ltd, Montreal Engineering Limited (Monenco), Williams Bros. Engineering Ltd. and Shawinigan Engineering Ltd.. Dr. Jack Clark was the manager of geotechnical engineering at NESCL.

4 NORTHERN PIPELINES

The first northern Canadian pipeline was the CANOL pipeline built during World War II to supply oil for the war effort. The 150 mm diameter pipeline was laid over-ground and operated less than two years before being abandoned.

Shortly after the initial major oil discoveries in the Mackenzie-Beaufort Basin and the Sverdrup Basin, studies were initiated for pipelines. The first proposal was a pipeline to support the Beaufort Delta Oil Project. However, the development of oil deposits and oil pipelines was soon overshadowed by the potential for natural gas, and the focus on natural gas pipelines began in about 1974.

Figure 2 shows some of the primary linear pipeline corridors in northern Canada that have been the subject of routing studies. Many potential routes and tens of thousands of square kilometers of terrain have been mapped for possible northern pipeline routes. Table 1

lists some of the important pipeline projects in northern Canada.

Figure 3 presents the commodity prices for natural gas through the time period of northern pipeline studies. There is an apparent linkage between changes in world natural gas prices and the onset and end of pipeline studies for some pipeline proposals. In general, it appears that the anticipation of higher gas prices led to the initiation of pipeline proposal studies followed by their abandonment during times of gas price decline. Figure 3 also shows that the later pipeline studies of the decades following the year 2000 were terminated specifically because these proposed pipelines (e.g. Mackenzie Gas Project) depended entirely upon the North American Market (Henry Hub in Erath, Louisiana) price. The North American natural gas price has been severely depressed in relation to the world price, because of the tremendous increase of United States "shale gas" production after 2007 (inset in Figure 3).

The following subsections describe the major constructed pipelines and paper pipelines proposed to bring hydrocarbons from northern Canada to market.

4.1 CANOL Pipeline

Oil was first discovered at Norman Wells (65.28°N) on 24 August 1920 (Bone and Mahnic 1984). At that time, the discovery represented the most northern discovery in the world. A small refinery was constructed in Norman Wells to provide petroleum products to communities along the Mackenzie River; during World War II oil production was expanded. To supply the war effort and as part of a larger Alaska defense strategy the US Army proposed that a pipeline be constructed from Norman Wells to Whitehorse and onwards to Alaska. The CANOL pipeline was constructed in 1942 to 1944. The 100 mm diameter and 960 km long pipeline, laid on wooden timbers on the ground surface, transported about 175 m³ of oil per day. The pipeline operated for about one year before being shut down and abandoned. The equipment, pump stations, and facilities were sold as surplus in 1947.

4.2 Polar Gas Pipeline Project

The Polar Gas Project, initiated in 1972, was intended to exploit natural gas reserves in the high Arctic. The project proponents included TransCanada Pipelines Limited (now TC Energy), Panarctic Oils Ltd., Tenneco Oil, the Ontario Energy Corporation (owned by the Ontario government) and PetroCanada (post-2009 subsidiary of Suncor Energy). Over the first decade the project spent over 80 million dollars on research and engineering studies (Kaustinen, 1983). The pipeline routes included east and west variations beginning in Melville Island and King Christian Island areas of the Sverdrup Basin. The eastern route would traverse the Arctic Islands landing on Somerset Island and traverse the Kitikmeot Region and Kivalliq Region along the west coast of Hudson Bay, connecting to the TC Energy mainline north of Lake Superior in Ontario. Another variation traversed the east coast of Hudson



Figure 2. Northern Canadian pipeline study corridors.

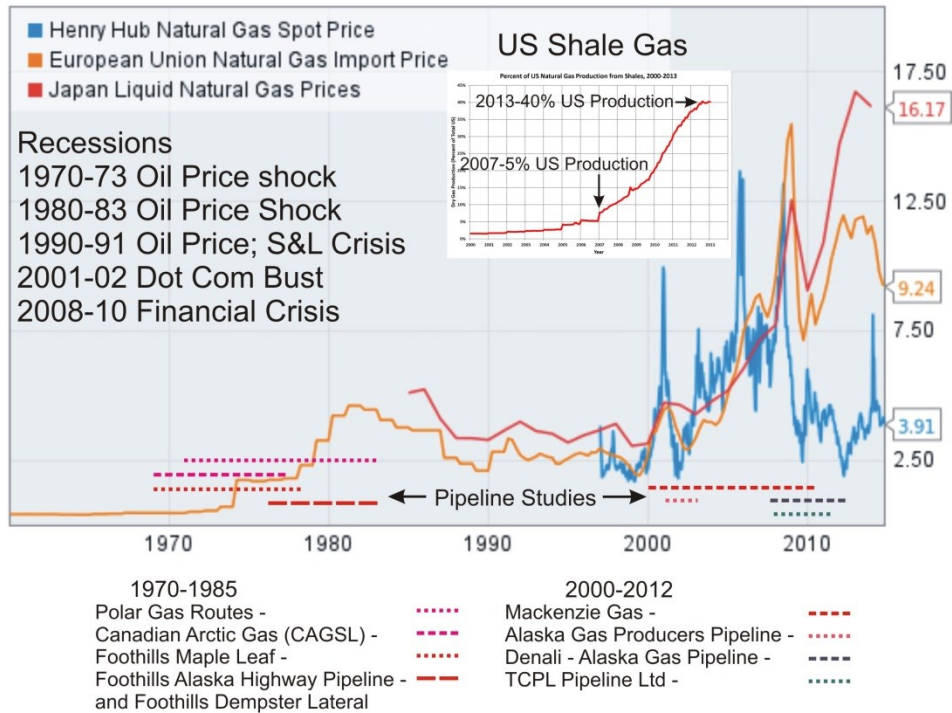


Figure 3. Historical trend in natural gas prices from the 1970s to present, showing the periods of major northern pipeline studies.

Table 1. Significant completed northern Canadian pipelines and pipeline studies.

Project	Routing	Study or Operating Dates	Comments
CANOL Pipeline*	Norman Wells to Whitehorse and Fairbanks, Alaska with laterals to Skagway, Alaska and to Watson Lake, Yukon.	-1942-1944	Constructed from 1942 to 1944 and operated from 1944 to 1945. 150 mm diameter oil pipeline, 960 km long, laid on ground.
Beaufort Delta Oil Project	Canadian Beaufort Sea to Edmonton	1971 - 1973	Initial proposal for a pipeline down Mackenzie Valley to carry oil from the Mackenzie Delta basin and the Beaufort Sea oil and gas fields. By 1974 interest in an oil pipeline superseded by planning for a gas pipeline. Not built.
Canadian Arctic Gas Project (CAGSL)	Alaska and Canadian Beaufort Sea to Lower 48 States	1969 – 1977	Initially formed as the Northwest Project in 1969 and joined by the Gas Arctic Group in 1972. Study abandoned following Berger Inquiry 1977 ten-year moratorium on pipeline construction in the Mackenzie Valley. Not built.
Polar Gas Project (East)	Canadian Arctic Islands along west coast of Hudson Bay to Manitoba, and into Lower 48 States.	1972 – 1980s	Initially proposed, but long water crossings led to early abandonment. Project participants included PanArctic Oils Ltd., TransCanada Pipelines Ltd. and several other companies. Not built.
Polar Gas Project (West)	Canadian Beaufort Sea through Mackenzie Valley into Alberta, and to Lower 48 States.	1972 – 1980s	Favored more direct route to access high Arctic island gas fields of the Sverdrup Basin and the Mackenzie Delta (the “Y-Route” option). Same consortium as for Polar Gas Project (East). Not built.
Maple Leaf Pipeline Project	Mackenzie Delta to Alberta, in competition to the Canadian Arctic gas project.	1974 – 1977	Conceived as a competitor to the CAGSL project, formed by Foothills Pipelines Limited. Project was abandoned following the Berger Inquiry. Not built.
Foothills Pipelines (South Yukon) Ltd.	Yukon-Alaska border to northern Alberta, generally following the Alaska Highway.	1976 – 1983	Initiated following the abandonment of the Mackenzie Valley pipeline route proposals. Received regulatory and political approval from both Canadian and United States governments. Pipeline easement is still valid and includes the Dempster lateral to bring Mackenzie Delta gas through the Yukon. Not built.
Alaska Highway Gas Pipeline Project	Prudhoe Bay through interior Alaska through Yukon, BC and Alberta with connection to California.	1977 – 1983	Initially proposed by Northwest Alaska and Foothills pipelines (South Yukon) Ltd. Pipeline project permitted by US and Canadian governments. Permits presently held by TransCanada Pipelines Limited. Not built.
Norman Wells oil pipeline*	Norman Wells NT to Zama, AB	1980 to present	Operating 300 mm diameter oil pipeline, owned by Enbridge Inc., began operations in April 1985 and continues to transport crude oil to Alberta.
Ikhil gas pipeline*	Ikhil gas field to Inuvik (50 km)	1998 to 2010	Operated a 120 mm diameter gas pipeline to supply natural gas to the Town of Inuvik, NT.
Alaska Gas Producers Pipeline Team (AGPPT)	Prudhoe Bay through interior Alaska through Yukon, BC into Alberta	2001 – 2002	Producers sponsored study of two routes, the over-the-top CAGSL route, and the Alaska Highway route. Not built.

Project	Routing	Study or Operating Dates	Comments
Arctic Resources Company	Prudhoe Bay along the Yukon Coastal plain to Mackenzie Delta and south through Mackenzie Valley to Alberta	2001 – 2002	Independent study proposing to operate the pipeline similar to a municipal infrastructure project, with 100% debt financing. Not built.
Mackenzie Gas Project	Mackenzie Delta to Alberta	2000 – 2010	Project producers include Exxon Mobil, Conoco Phillips, and Shell Canada. Received Federal regulatory approval in 2010. Not built because of unfavorable economic conditions. Permit to build lapsed in 2017.
TransCanada Pipelines Limited	Prudhoe Bay through interior Alaska and across Yukon, BC into Alberta	2008 – 2011	Project study under enabling legislation by Alaska State (Alaska Gas Inducement Act). Project is a resurrection of the Foothills Pipeline Alaska Highway project. Not built.
Denali – The Alaska Gas Pipeline	Prudhoe Bay through interior Alaska through Yukon, BC into Alberta	2008 – 2012	Project study sponsored by ConocoPhillips and BP Exploration. Pipeline study in competition with the TransCanada Pipelines Limited project. Not built.

* Northern pipelines constructed and operated.

Bay through Quebec. The western or “Y” route would cross Banks or Victoria Islands to Melville Island, joining a routing to the Mackenzie Delta, or from there extending southeast, west of Hudson Bay, and connecting with the TC Energy mainland in northern Ontario (Figure 2).

4.3 Canadian Arctic Gas Study Limited

The Canadian Arctic Gas Study Limited (CAGSL) was initiated by a consortium of twenty seven companies in Canada and Alaska including producer companies such as Exxon Inc., BP/SOHIO, Imperial Oil, Gulf Oil Canada, and Shell Canada Ltd., and transmission companies and distribution utility companies, such as Columbia Gas Transmission, Michigan Wisconsin Pipeline, Pacific Lighting Gas Development, Alberta Natural Gas, Consumers Gas, Union Gas, and TransCanada Pipelines Ltd. The intent of the project was to design and construct a 1.2 m diameter gas pipeline from Prudhoe Bay Alaska across the Alaska and Yukon north slopes, to the Mackenzie Delta in the Northwest Territories, where it would collect Canadian natural gas. The pipeline route would then turn south and follow the east side of the Mackenzie River valley to near Fort Simpson where the pipeline would cross the Mackenzie River and continue southward to Alberta.

The engineering work for this project was conducted by the NESCL consortium described in Section 3. The work covered the entire breath of studies necessary for the project. Over 10,000 boreholes were drilled along the Canadian portion of the route, and various test sites were constructed and operated. Other studies included Northwest Territories and Yukon Territory river studies for ice-breakup, borrow site investigations, wharf studies, and many environmental terrain and wildlife studies.

Several test sites were constructed in both Alaska and Canada. One notable test site in Canada was the Calgary frost heave facility. This was constructed on the north side of 32 Avenue NW opposite the University of Calgary. Initially constructed in 1974 by CAGSL, it was taken over by Foothills Pipeline Limited in 1977. This project consisted of six full-size 1.2 m diameter pipe sections, each about 12 m long. The intent of the tests was to assess pipeline behaviour under frost heaving conditions and to evaluate potential mitigation measures. This site was particularly important as the soil (so-called Calgary silt), is highly susceptible for ice lens formation under freezing conditions and access to free water (Carlson, Ellwood, Nixon and Slusarchuk, 1982).

Another test site was the San Sault Rapids near the Mackenzie River north of Norman Wells. This facility provided the means to evaluate and determine the stability of pipelines in permafrost, the stability of various foundation types for aboveground structures, pipeline effects on surface cover, Arctic drainage problems, and study construction methods, materials, and equipment which might be used in an Arctic system (Patman, 1971).

The CAGSL project was abandoned in 1977 after the environmental and socio-economic review “The Mackenzie Valley Pipeline Inquiry” (often referred to as the Berger Inquiry, after the commissioner of the inquiry Justice Thomas Berger (1977)) recommended a 10-year moratorium on pipelines in the Mackenzie Valley until land claims were resolved.

4.4 Maple Leaf Pipeline Project

The Maple Leaf pipeline project was formed in about 1974 as a competitor project to CAGSL; however it was limited to the transport of Canadian gas from the Mackenzie Delta. It was conceived by Foothills Pipelines Limited, a partnership between Alberta Gas

Trunk line and Westcoast Transmission. Klohn Leonoff Ltd. and Northwest Hydraulics Ltd. provided geotechnical and hydrotechnical engineering.

As with the CAGSL project, the Mackenzie Valley pipeline moratorium recommended by the Berger Inquiry led to the immediate cancellation of the project in 1977.

4.5 Foothills Pipelines (South Yukon) Limited

The Foothills project began in 1976. The pipeline route would take natural gas from Prudhoe Bay to the Alaska – Yukon border near Beaver Creek and then would traverse the southern Yukon approximately parallel to the Alaska Highway and extend into northern British Columbia. To access natural gas from the Mackenzie Delta, a separate pipeline along the Dempster Highway (known as the Dempster lateral) would connect to the Foothills mainline near Whitehorse.

Following the end of the CAGSL project, the Foothills pipeline project gained significant momentum. The Alaska Highway Pipeline Inquiry (K.M. Lysyk, Chairman) beginning April 1977 was instituted by the Canadian Government to assess the social and economic impacts from gas pipeline construction and operation along the proposed routing of the Foothills pipeline in the Yukon (Lysyk et al., 1977). This inquiry ended July 1977 and on August 2, 1977 the project was approved by the National Energy Board (now the Canadian Energy Regulator) and Canada and the United States signed the *Canada-United States Agreement on Principles Applicable to a Northern Natural Gas Pipeline*. The following year the route was certified and regulatory jurisdiction was vested in the Northern Pipeline Agency.

During the late 1970s and early 1980s considerable research was conducted to address issues of thaw settlement and frost heave. In addition to the test facility in Calgary, a large test facility was operated at Quill Creek, Yukon.

Although the pipeline was never built, the certified right-of-way exists today and was used for a subsequent study in the 2000s. This study (TransCanada Pipelines and Alaska Gas Producers) also proposed to bring Alaska gas to southern markets.

4.6 Enbridge Norman Wells Pipeline

In the late 1970s an oil pipeline from Norman Wells to northern Alberta was proposed and eventually approved by the National Energy Board (now the Canadian Energy Regulator). Construction of the 886 km long, 305 mm diameter fully buried pipeline began in 1982 and was completed in early 1985, with first oil flowing to Zama, northern Alberta, in April 1985.

This pipeline is the first fully buried pipeline in permafrost terrain in the world. It was also the first pipeline design using limit state (strain based) design methods. The route crosses 140 defined water crossings and over 150 significant slopes, of which about 50 are insulated with woodchips to reduce the rate of long-term thaw.

4.7 Ikhil Pipeline

The Ikhil gas pipeline is a 50 km long small diameter gas pipeline that extended from the Caribou Hills area of the Mackenzie Delta to the Town of Inuvik. It was initiated in 1995 and began operation in 1999. The impetus for the pipeline was to provide natural gas for power and heating in Inuvik, replacing the existing diesel electrical generation and imported home heating oils. The gas supply was expected to last over 15 years, hopefully long enough for the larger Mackenzie Delta gas supplies to be exploited and transported past Inuvik. Unfortunately, water entered the gas well, which prematurely curtailed the gas supply in about 2010.

The pipeline was fully buried in continuous permafrost except at one stream crossing where the pipeline is above ground supported on steel support trusses (KavikAXYS Inc. 2007).

4.8 Mackenzie Gas Pipeline

In 2000 Imperial Oil Ventures Limited and partners including Exxon Mobil, Conoco Phillips Canada, Shell Canada and the Aboriginal Pipeline Group (partially funded by TransCanada Pipelines Limited) proposed a resurrected version of the Mackenzie Valley portion of the CAGSL project. The pipeline would transport up to 34.3 million cubic metres of natural gas over 1,200 km from three anchor gas fields to northern Alberta. A smaller natural gas liquids pipeline would be built from the Mackenzie Delta to Norman Wells where the liquid pipeline would merge with the existing Norman Wells oil pipeline and continue to Zama, Alberta.

The project went through five years of regulatory hearings before a Joint Review Panel (JRP), comprising the National Energy Board and environmental reviewers. The JRP approved the project in 2010. However, by the time of approval was gained North America gas supplies were being increased by exploitation of shale gas (inset in Figure 3) and the pipeline project was deemed uneconomic. In 2017 Imperial Oil and their partners cancelled and abandoned the project, relinquishing the permit.

4.9 TransCanada Pipelines and Alaska Gas Producers

From the early 2000s through about 2015 several pipeline studies were initiated to bring Prudhoe Bay gas to North American markets. These studies were primarily funded by the Prudhoe Bay producers. The routes considered were very similar to the routes proposed in the 1970s, being an “over-the-top” route, similar to CAGSL, and a route through central Alaska and then southwest through the Yukon and northern British Columbia along the Alaska Highway. The northern coastal route had numerous issues including the need to traverse the Arctic National Wildlife Reserve. The reserve was established in 1960 and predated the CAGSL routing, and the pipeline routing in the 2000s attracted even more opposition including a

bill in the Alaska legislature forbidding pipeline routing through the reserve.

The southern route within Canada followed the Foothills Pipeline Ltd. alignment and indeed the company (now owned by TC Energy) was an active partner in one of the studies. Using the Foothills right-of-way, which was still a registered easement, required the reestablishment of the Northern Pipeline Agency.

These projects proposed to construct pipelines with diameters of 1.2 m to 1.32 m. The gas volume transported would be in the order of 110 million cubic metres of gas per day – three times the volume of the proposed Mackenzie Gas Project.

By the mid-2010s the economics of the project was doubtful particularly in light of the shale gas development in continental United States. The proponents then switched the project to an in-state pipeline with an LNG export terminal near Cook Inlet with export markets in Asia where the LNG price was much higher than in North America.

5 LESSONS LEARNED

Significant advances in the understanding of permafrost and periglacial processes and the behaviour of pipelines in permafrost were spurred by the planning and engineering designs for these northern pipelines. The University of Alberta, in particular, became a hub for northern pipeline research. Our understanding of frost heave, slope stability, thaw consolidation theory, and many other aspects of pipelines in permafrost geotechnique stem from university graduate research. The Geological Survey of Canada, the National Research Council of Canada, Carleton University and other institutions also provided important contributions in support of these projects.

Important contributions were also added by engineering and environmental consultants. The development of numerical models to predict changes in the geothermal regime of permafrost due to pipeline construction and operation were led by several Canadian geotechnical engineering consultants. Environmental reclamation, revegetation and erosion control methods were advanced as a result of field studies. The legacy of this work, first started nearly 50 years ago is still of great value today. Oswell (2011) provides additional lessons learned from the Canadian northern pipeline experience.

Table 2 lists some of the important contributions to permafrost engineering and northern pipeline design.

6 CONCLUDING REMARKS

The authors wish to acknowledge contributions to this paper received from Fred Claridge, David Morrow and others, whom the authors have worked with over the past decades. As anyone who tries to summarize the history of past projects knows, discovering the full story is difficult. This is particularly challenging in the case of northern pipelines, where the work was carried out for major oil companies under confidentiality, and some of the data is still regarded as proprietary. In the end,

having gaps and neglecting contributions is unavoidable, for which we apologize.

Table 2 Summary of some important contributions to permafrost engineering and northern pipeline design.

Topic/area	Selected References
Frost heave	Slusarchuk., Clark, Morgenstern, Nixon and Gaskin (1978) Carlson, Elwood, Nixon and Slusarchuk (1982) Konrad and Morgenstern (1981) Konrad and Morgenstern (1984)
Geothermal modelling	Hwang (1976) Hwang (1977) Nixon (1983) Nixon (1986)
Slope stability	McRoberts and Morgenstern (1974) Hanna and McRoberts (1988)
Thaw consolidation	Morgenstern, and Nixon (1971) Nixon and Morgenstern (1973)
Thaw settlement	Palmer (1972) Watson, Rowley and Slusarchuk, (1973) Hanna, Saunders, Lem, and Carlson (1983) Johnson, McRoberts and Nixon (1984)
Trenching in permafrost	Hayley, Inman and Gowan (1984) Saunders (1989)
Winter road construction and erosion control	Adam (1978) Claridge and Mirza (1981)

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