Engineering in Canada's Northern Oceans

Research and Strategies for Development

A Report for the Canadian Academy of Engineering

Final

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Executive Summary

The areas of study are Canada's Northern Oceans, the Arctic and the Atlantic, and waters and seas that are part of or adjacent to these oceans. These include the waters within and around the Canadian Arctic Archipelago, the various islands of which are separated from one another and the continental mainland by a series of waterways comprising the Northwestern Passages. Canada's Northern Oceans cover a vast area stretching 4000km from the waters off Newfoundland populated by icebergs to the remote Arctic Ocean off the northern coast of Ellesmere Island and from there 2000km southwestward to the Beaufort Sea.

The presence of ice in the Northern Oceans has always been the major challenge facing Canadians living and venturing into the region. First Nations developed very sophisticated ways of living in the North and of making use of ice and snow. Explorers and developers who came later quickly realized how great an impediment ice was to their ambitions. Only in the last 70 years or so has the application of scientific knowledge and engineering methods enabled transportation pathways and certain development activities to proceed – albeit with higher costs than in the South. With current trends ice may indeed become less formidable but it is our perspective that ice will continue to dominate engineering in the Northern Oceans.

The search for and development of mineral resources commencing in the mid-twentieth century presented both challenges and opportunities for Canadian engineers. In addressing these opportunities, the case histories of which are documented in this report, Canadians became world leaders in engineering for northern oceans and have applied their skills in both Canada and elsewhere.

A survey of this expertise has been conducted as part of this study. Despite less activity than in the past, Canada's northern engineering ability still exists and is being exercised, but many of the experts are approaching retirement. The supply of younger engineers in this specialized area has been adversely affected by the cycles of resource development. This challenge is discussed in the study and solutions are offered.

Why are these issues important for Canada? This study suggests several reasons.

- There are significant resources in Canada's North which, if developed responsibly, will create value for Canadians.
- In enabling northern developments, employment and training opportunities for Canada's Northern residents will be enhanced and they will also be empowered by participation.
- Furthermore, maintaining and enhancing our knowledge base also gives Canadian engineers and engineering firms a competitive advantage elsewhere in the world in both providing consulting services and in creating joint ventures.

- Finally, the ability to maintain sovereignty and to understand and respond to climate change in the North will be enhanced by maintaining and exercising our Northern Oceans engineering capabilities.

The technical emphasis of this report is the study of engineering needs for future development in northern marine waters. The focus is primarily on natural resource development and infrastructure needs for other activities such as Arctic community re-supply, Arctic shipping, and maritime safety and security.

The study group conducted a brief review of climate change and in particular its influence upon shipping. Conditions in the Northwest Passage are known to be highly variable from year to year. The Intergovernmental Panel on Climate Change (IPCC) finding of a warming trend and thinner ice is accepted, but any use of this trend in planning of transportation and engineering activities must be considered in the light of year-to-year variability, and the possibility of old ice in the passageways of the Northwest Passage. In brief, IPCC findings are accepted but their interpretation in Arctic engineering is far from straightforward. Engineers must account for all relevant uncertainties in their planning.

The study continues with a review of recent reports, including two from the Centre for the North (CFN 2011, 2013). These reports emphasize the importance of climate change, infrastructure, emergency response and search and rescue, as well as commodity prices, in northern development. Climate change will improve the accessibility of northern marine waters; an increase in shipping is possible but there are complicating factors. It is concluded that "the way that the risks and benefits of economic development are weighted and managed must make sense to Northerners, keep their interests front and centre, and effectively capture the Northern context." Leveraging public–private cooperation and partnerships is advocated. "Boom-bust" issues, for instance when mining activities create substantial activity, and then decline, can be an important issue in planning. Transportation infrastructure is significantly more expensive to develop in Northern communities than in the South, and at present is sparse. Warming, permafrost degradation and declining viability of winter roads must be taken into account in new designs. The importance of marine transportation is emphasized. The Centre for Arctic Resource Development in their Arctic Development Roadmap (CARD 2013) focused on the oil and gas industry and consulted extensively with that industry. The principal issues raised were environmental protection, ice management, ice mechanics and loading, station-keeping in ice and environmental characterization.

For the subject report an inventory of Canadian centres oriented towards Northern research has been carried out, together with a detailed review of present-day Canadian expertise. Canadian contribution to codes and standards, many of them international, has been summarised. The report includes a set of case studies of Canadian involvement in engineering for the following areas: Beaufort Sea, East

Coast of Canada, Caspian Sea, Barents Sea, Voisey's Bay, Arctic islands and pilot production, Arctic Pilot Project. An inventory of mineral resources and port infrastructure has also been undertaken. Barriers to development are seen as transportation, infrastructure, energy and people.

Past use of the Northwest Passages has been reviewed, including the voyage of the S.S. Manhattan, as has Canada's icebreaker design and construction during the 1970s. The Canmar fleet, in particular the *Kigoriak*, as well as the Beaudril fleet have been reviewed. Canada's Emergency Evacuation and Rescue (EER) capability is viewed as being a world leader. Recent shipping activities have been centred on the MV *Arctic*, MV *Umiak*, MV *Nunavik*. In Canada's waters, destination shipping (for example, shipping associated with mining activities) is seen as the important activity. Canadian infrastructure to support northern marine activities is sparse in contrast to Russia, which has year round activities and considerable infrastructure; Russia continues to expand its capability for Arctic marine operations.

Technical uncertainties and barriers to future resource developments are discussed in this report. Several of these are already being addressed by industry and also through collaborative activities with institutes such as C-CORE, CARD and NRC, and universities such as Memorial. Federal funding is channeled mostly through NRC and universities. High priority engineering topics worthy of additional, collaborative and imaginative work include:

1. *Ice Mechanics and Loading*

   The crux of Arctic offshore engineering is to understand ice mechanics and how ice generates loads on platforms and vessels. Local and global ice pressures are needed for design of both. There has been significant progress in this field by Canadian engineers who have used large-scale measurements taken to date to develop new theories and methods. The size effect is most important in global design and would benefit significantly from more full scale testing and measurements with thick ice. Improved information on forces in pack ice is also seen as a research need, as well as the mechanics of interaction of sloping structures with thick ice.

2. *Floating Platforms in Ice*

   In deeper waters in the Beaufort and Labrador Seas, subsea production with pipelines back to shallower water is one possible scenario. Floating platforms will be needed for drilling and possibly for early production. There is a need to make these floaters as ice tolerant as possible in order to extend the drilling season and especially for relief well drilling. They would be disconnected if ice conditions become too severe. The ice can also be managed to reduce ice loads. How the degree of ice management affects the ice loads and how to estimate them is still a subject of research; there is a continued need to address this issue. Forecasting of ice and metocean conditions is an important component in these operations, including such factors as pressured ice and sudden changes in the direction of ice movement.

3. *Arctic Shipping*

   Shipping is required for community access, tourism and transportation of resources. Ice loads on ship hulls in heavy ice, and efficient ice-worthy propulsion systems continue to be a worthy research topic. Navigational infrastructure will need attention.

4. *Terminals and Harbours*

   In ice covered regions terminals and harbours have different design and operational problems from those in the South. Dock facilities and berthed vessels have to be designed for ice interaction. If too much protection is provided by enclosures, ice build–up due to repeated ships transits can be a problem and ice management becomes critical.

5. *Safety and Environmental Protection*

   Escape and evacuation from vessels and platforms in ice is an issue unique to the North. Work has been underway on this topic, but improvements will be key to maintaining safety in harsher regions. Drilling of a "same-season relief well" poses difficulties as operations move further north, with shorter drilling seasons and more difficult ice conditions. The issue of oil spills is best addressed by prevention – which is dependent on sound design and impeccable operating methods. Even so, if oils spills do occur, it is paramount to understand their impacts and how to mitigate them. Ice can be advantageous in containing a spill, but recovery of the oil can be more difficult.

6. *Environmental Characterization*

   Safe and efficient design of engineering structures and vessels also depends on knowing the types of ice and other environmental parameters prevailing in an area. Climate change brings additional uncertainty in defining extreme ice features. Methodologies are needed to address this uncertainty. Understanding and predicting how multi-year ice will change in both occurrence and thickness is highly important.

Northern involvement and education deserve attention within the context of engineering for the Northern Oceans. Traditional knowledge is recognized to play a role in engineering and that there is benefit from close relationships between engineers and Northern residents through entities such as the Centre for the North, which provides a forum for research and dialogue on Northern and Aboriginal issues.

There is a high percentage of young people in the North, and future developments can provide them with meaningful employment. Outreach programs are recommended to raise awareness of science and engineering amongst Northern schoolchildren. Early awareness and creation of interest and excitement surrounding potential future engineering and scientific projects is a foundation on which to build an educated population who can then be meaningfully involved. Improved access by Northerners to educational facilities in engineering and technology is seen as a priority, and we advocate the commencement of instruction in engineering and technology at CHARS linked to expertise in other Universities in Canada, for example Memorial University. The concept could be similar to the Ny-Ålesund research facility in Svalbard, which is managed by the Norwegian government.

One of the themes of this study has been to show that significant advances in knowledge flow from "doing" rather than "discussing". Resource developments will occur without intervention, if the economics are favourable and regulations are fair. Nevertheless, there are infrastructure, collaborative research and community projects which, if encouraged and funded, can enhance Northern engineering capabilities. The team proposes for consideration several "visionary" projects and programs listed below.

1. *Arctic LNG—Clean Green Fuel for the North*

   The Arctic has an abundant supply of natural gas both in the Beaufort Sea region and in the Arctic Archipelago. Arctic communities and activities need fuel. It is proposed to develop an Arctic liquified natural gas (LNG) public–private partnership to supply LNG both for both fuelling government Arctic operations and supplying local community needs. This would provide clean green Arctic fuel that would, for example, allow year round icebreaker operations.

2. *Mobile Arctic Engineering Research Platform*

   In this concept an iceworthy ship would be developed to be the engineering experiment itself, rather than a platform for science laboratories. Ice transit experiments, hull and propeller loads, study of towing of arrays in ice, ice management strategy development, experiments to develop support of sub-sea developments in ice are possible functions, with Nanisivik as a possible northern base.

3. *Canadian Arctic Railway along the McKenzie Valley from Hay River to Inuvik*

   A Canadian Arctic Railway, possibly fueled by LNG, would provide a two-way system that could be used to deliver materiel for northern construction, as well as fuel and other essentials for local communities at present serviced by summer barge traffic on the McKenzie River. The system could bring Arctic oil to Southern markets, and the rail road would provide a strong logistics link to the Western Arctic, improving infrastructure and reinforcing Canadian Arctic sovereignty. Further, the system would allow for development of other natural resources along its route, such as mining and forest products.

4. *International Arctic Ocean-Space Engineering Experimental Station (IAOSEES)*

   A permanent base is proposed on Hans Island, which is currently disputed territory in the Kennedy Channel between Canada and Denmark. The IAOSEES (pronounced *Eye-Oh-Seas*) would be jointly managed by Canada and Denmark as a shared facility available to members of the Arctic Council. There is a need for large scale experimentation to further advance Arctic marine and offshore engineering.

Arctic sovereignty requires a strong presence in the region. A sovereign state is represented by one centralized government that has supreme independent authority over a geographic area. There are responsibilities associated with this authority. For an Arctic state in the 21st century, these responsibilities can only be satisfied by the extensive use of technology, including ships, aircraft and remote monitoring systems. The polar icebreaker CCGS Diefenbaker will be available when completed in some years' time; in the meantime Canada has very limited capability. The Arctic Offshore Patrol Vessels now being designed and built have limited ice transiting capability. Canada is ill-prepared to address any future challenge to its sovereignty in the Arctic. A parallel approach to exerting sovereignty is to be economically and scientifically active in the region. In this context, the initiatives suggested above and detailed in this report would achieve much towards this end.

Contents

1 Overview of Canada's Northern Oceans

1.1 Introductory Comments

Three great oceans – the Atlantic, the Arctic and the Pacific – surround Canada (Figure 1.1). The concern of the present study is the two northern oceans, the Arctic and Atlantic. The study includes the waters that are part of these oceans: the Beaufort Sea as part of the Arctic Ocean; the Labrador Sea and the Hudson and Baffin Bays, as part of the Atlantic Ocean, as well as the Davis Strait, a northern arm of the Labrador Sea. The study includes also all of the waters within and around the Canadian Arctic Archipelago. The various islands are separated from each other and the continental mainland by a series of waterways comprising the Northwest Passages.

The presence of ice in the Northern Oceans has always been the major challenge facing Canadians living and venturing into the region. Ice can be present in the form of various ice features that need to be understood by engineers and mariners. In the Arctic Ocean, during a typical nine-month winter, ice will form and grow to a thickness of about 1.5–2m. Except close to shore, the ice moves under the action of winds and currents and can be subject to pressure which causes pressure ridges to form. Depending on the degree of ice pressure and the thickness of the ice at their creation, Arctic pressure ridges can be over 40m thick at their extreme; they are significant obstacles to ships and can impose significant loads on platforms. When they ground in shallow water, they scour the sea floor, creating hazards to pipelines.

In southern Arctic waters, during the summer, the ice formed in the prior winter may melt away. In more northerly parts, the ice normally survives the short summer and is subject to further growth during the next winter. Several cycles of this freezing and melting leads to the formation of multi-year (MY) ice, which in the High Arctic will achieve an equilibrium thickness in the range of 4–5m. Pressure ridges are subject to similar processes. In the south they can melt away each summer, but in the north they consolidate into solid multi-year ice ridges. These ridges are not as thick as first-year (FY) ridges (say about 20–25m thick), but are of solid ice and represent very severe ice features for design.

The amount of MY ice in the Arctic Ocean varies from year to year and is especially sensitive to the export of Arctic ice through the Fram Strait. As will be discussed later under climate change, in recent years this export appears to have been higher than in past decades, resulting (together with the warming trend) in an overall thinning of Arctic Ocean ice.

Other ice features can also exist in the Northern Oceans. These include icebergs and ice islands, both of which are also very formidable for the design and operations of platforms and ships. Icebergs are not common in Canada's Arctic Ocean, but the occasional ice island occurs. Ice islands are calved from ice shelves in the fiords of the north coast of Ellesmere Island. These ice shelves grow slowly but can attain a thickness up to 60–100m. After calving, ice islands circulate with the Arctic pack ice and over time become thinner. Nevertheless, even at 30–40m thickness and several kilometres across, they are clearly very challenging features for design and are to be avoided by vessels.

Icebergs occur mostly off Canada's East Coast all the way from Ellesmere Island to Newfoundland. They originate from the glaciers of Greenland and Northern Canada. Icebergs can be several hundred metres in draft and millions of tonnes in mass. Again, they present a formidable challenge to offshore platform design and operations.

Regions such as Hudson Bay and the Gulf of St. Lawrence are subject only to annual ice. Even so, this ice can grow up to 1–1.5m thick, while pressure ridges up to 15–20m can occur within the pack.

During the late 1950s and 1960s the Canadian Arctic was of strategic geopolitical importance, and most research related to military requirements for surveillance and logistics. In the 1970s and 1980s the driver for research was exploration for and potential production of oil and gas and minerals. The 1969 voyage of the SS Manhattan through the Northwest Passage was a stimulus for research relating to the safety of shipping in the Canadian Arctic. The work focused on ice climatology and naval architecture (hull strength and power requirements). The petroleum industry's interest in offshore oil and gas exploration drove extensive research activities into the ice environment, ice effects on offshore drilling activities and development of suitable engineering solutions. This research was funded by and largely conducted by staff within the petroleum industry. The 1990s saw reduced research in the Canadian Arctic, but this has again increased in the 21st century.

The technical emphasis of this report is the study of engineering needs for future development in northern marine waters. The focus is primarily on natural resource development and infrastructure needs for other activities such as Arctic community re-supply, Arctic shipping, and maritime safety and security. These activities are considered from the perspective of engineering design needs. Design with regard to ice loading is governed by international codes and standards, for example *ISO 19906:2010, Petroleum and Natural Gas Industries—Arctic Offshore Structures* and the *IACS—Unified Requirements for Polar Class Ships*. The latter applies to ships constructed of steel and intended for navigation in ice-covered polar waters, and is in the process of being introduced into the *IMO Polar Code*. In Canada the relevant standard is embodied in the *Arctic Shipping Pollution Prevention Regulations* (ASPPR).

The codes and standards just described include methods for design and construction, and the present report is composed as a constructive input for future development of these documents. Canadian engineers played key roles in the development of the ISO and IACS codes. This report also deals with infrastructure needs, as well as the remoteness and extreme weather conditions of arctic regions. Climate change is modifying ice conditions, the engineering implications of which will be considered. The lack of geological and hydrographic data in northern regions is also addressed.

Engineering expertise and design methods developed in the past in Canada have been successfully applied to other areas such as the Caspian Sea, the Barents Sea, the Chukchi Sea and many other regions including the Kara Sea in Russia.

This study makes recommendations on the investments in research required to develop engineering approaches and codes for safe and efficient developments in Canada's Northern Oceans and will include perspectives on the need to educate and train engineers in Arctic technologies. It is intended to be complementary to other initiatives such as those underway by Centre for The North and the Council of Canadian Academies. Its focus is on engineering and its role in future activities.

Figure 1.1: Canada's northern waters. (http://atlas.gc.ca/)

1.2 Climate Change

The Intergovernmental Panel on Climate Control (IPCC) Fifth Assessment Report (IPCC, 2013) notes the following:

- Warming of the climate system is unequivocal, and has been ongoing since the 1950s.
- The atmosphere and ocean have warmed, the amounts of snow and ice have diminished, sea level has risen, and the concentrations of greenhouse gases have increased.

A summary of IPCC 2013 is given in Appendix A to this report and its findings are well accepted by the writers of the present report. At the same time, there are various factors that introduce uncertainty, which must be taken into account in an engineering assessment. Some of these are summarized in the following sections.

It is not the intent of this study to review and debate the various forecasts of climate change in the North. Changes in the ice regime have occurred in some regions but not in others. How the future will unfold is subject to uncertainty, and this is the challenge to Northern engineering activities.

1.2.1 Sea Ice and Forecasts

Figure 1.2 shows the decline in September and February sea ice cover in the Arctic. The trend is indicative of a strong reduction in summer sea ice cover, but there are many factors that should be taken into account in terms of making an engineering assessment. In Figure 1.2, most of the decline occurs after about 1997. There are some grounds to believe that flux through Fram Strait was involved in the decline in subsequent years. Warming is undoubtedly a factor in the reduction of sea ice, yet flushing through Fram Strait is also a well-accepted factor, and for example acknowledged in work of Stroeve and others (2014).

Smedsrud et al. (2011) state that "The high sea ice area export must have been a significant contributor to the low September sea ice covers observed in recent years. The sea ice area export in 2009 and 2010 was lower than for the previous years, 2005, 2006, 2007 and 2008, perhaps indicating that the sea ice export may return to more moderate levels again soon." The engineer has to consider all potential adverse future scenarios for design; the possibility of ice export through the Fram Strait returning to normal (with subsequent build-up again of multi-year ice) cannot be discounted, even though this may be considered unlikely by some. Figure 1.3 shows the ice extent for the months June to October and that 2012 had the largest summer retreat since satellite observations were available. Figure 1.2 shows the large variability and that the summer retreats were not as great in 2013 and 2014. The rate of decline and variation in ice extent is much smaller in the winter months than in the summer.

The literature indicates that there is considerable uncertainty in forecasts of arctic sea ice cover; see Stroeve et al. (2014) and Wilson et al. (2004), for example. The latter reference considers five Global Climate Models (GCMs) and notes that the Canadian model forecast the disappearance of summer ice by 2070, while the National Center for Atmospheric Research (NCAR) model forecast the ice extent remaining constant (Walsh and Timlin, 2003). Wilson et al. consider the Northwest Passage (NWP) shipping routes (Figure 1.4). Sea ice predictions were considered to be less dependable and indeed inadequate for the Canadian Arctic Archipelago and the passageways between the islands. Some areas such as M'Clure Strait can remain blocked by old ice in most years.

This is supported by the work of Melling (2002, 2013). Melling (2002) studied pack ice and relevant climate variables of the Canadian Arctic Archipelago north of Parry Channel. Pack ice is present within the Canadian Arctic Archipelago throughout the year. The southern and eastern regions may clear wholly or in part by late summer; ice concentrations in the Sverdrup Basin are always high. The extreme difficulties of navigation and the harsh climate have inhibited study of the marine cryosphere. "Scientific knowledge is superficial and incomplete".

Multi-year ice is formed in the zone of heavy ridging along the periphery of the Beaufort gyre and is imported into the Sverdrup Basin. Melling (2002) suggests that warming climate might not bring lighter ice conditions to northern Canadian waters. Very heavy multi-year ice is at present blocked in winter by pack ice in the northwestern entry points and the southern exit from the Sverdrup Basin. Thick, heavily ridged multi-year ice from the Arctic Ocean is slowed down by this process in its movement through the Canadian Arctic Archipelago. In a warmer climate, the ice bridges that ring the Sverdrup Basin will be weaker, and heavy ice will move more quickly through the Basin. The flux to Northern shipping routes will increase with increased multi-year ice.

In the 2013 paper, Melling showed a comparison of mean values of thickness from systematic drilling in the area north-west of Penny Strait during the 1970s (Melling 2002) with the range of values estimated for the same time of year from the sonar measurements in 2009. The average thickness of sea ice in the vicinity of Penny Strait was found to be similar to the values of the 1970s. See Figure 1.5. These recent data do not demonstrate a change in thickness of the predominantly multi-year ice in this area during the last 40 years. Howell et al. (2013) confirmed that the presence of MY ice in the Canadian Arctic Archipelago originating from the Arctic Ocean has been maintained and increased since 2005, attributed to increased open water area within the Canadian Arctic Archipelago that has provided more leeway for inflow to occur. Pizzolata et al. (2014) studied possible correlation between the decline in sea ice and shipping activity; between 1990 and 2012, statistically significant increases in vessel traffic were observed within the Northern Canada Vessel Traffic Services Zone (NORDREG), but overall the correlations were not strong.

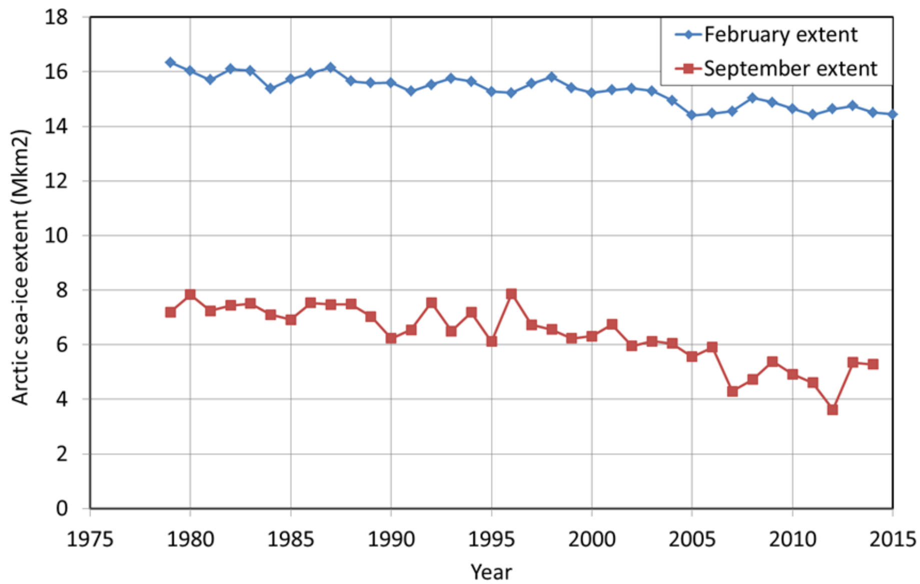

Figure 1.2: Arctic sea ice extent
(ftp://sidads.colorado.edu/DATASETS/NOAA/G02135/)

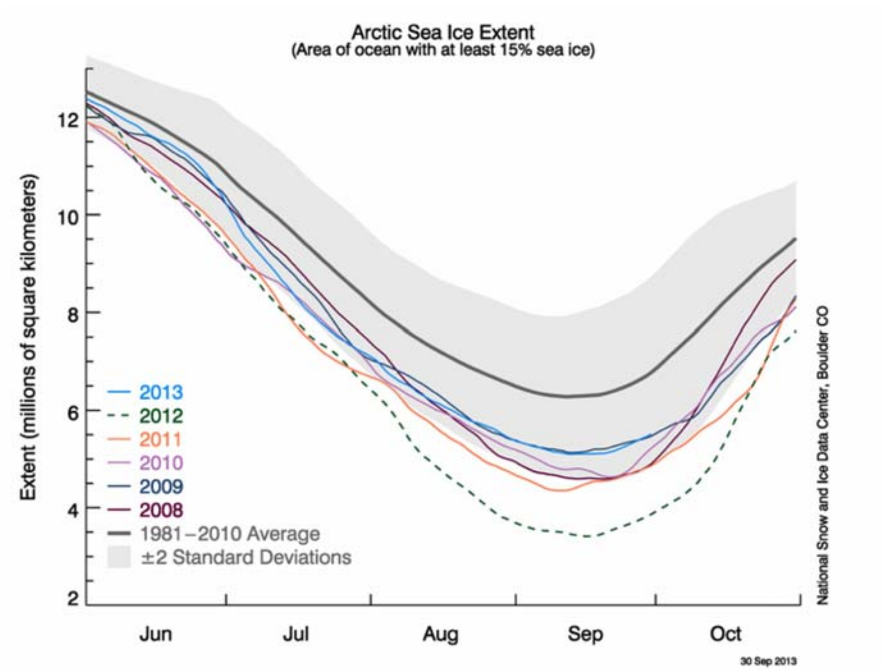

Figure 1.3: Arctic sea ice extent as of September 30, 2013, with daily ice extent data for the previous five years. The grey area around the average line shows the two standard deviation range of the data.
(http://nsidc.org/arcticseaicenews/2013/10/a-better-year-for-the-cryosphere/:)

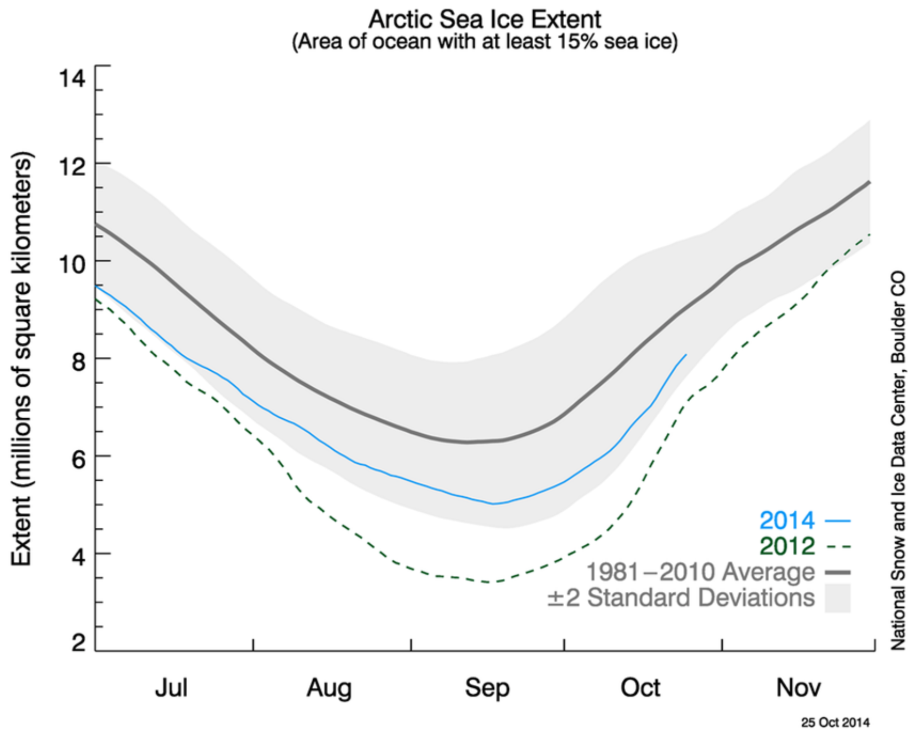

Figure 1.4: Arctic sea ice extent graph updated as of October 25, 2014 (http://nsidc.org/arcticseaicenews/2013/10/a-better-year-for-the-cryosphere/:)

Figure 1.5: The Northwest Passages

(http://en.wikipedia.org/wiki/Northwest_Passage)

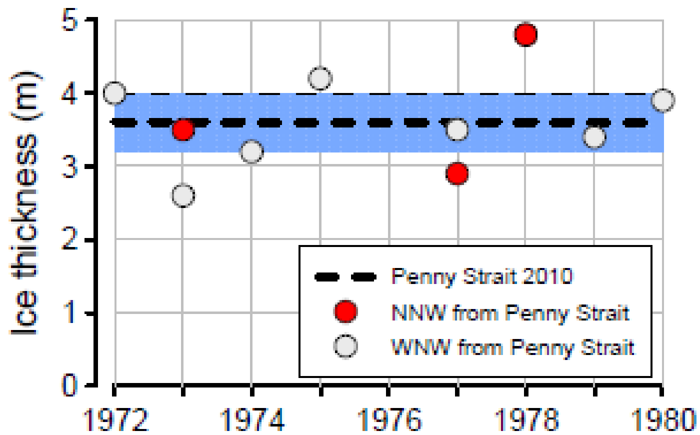

Figure 1.6: Track-mean ice thickness from drill-hole surveys of northwest of Penny Strait during late winter in the 1970s, compared with values based on 2009 data [shaded band is ±δ] (Melling 2013)

1.2.2 Uncertainty, Variability and Possible Trends

The prior discussion highlights the variability and uncertainty associated with ice conditions. The conditions in the Northwest Passage are known to be highly variable from year to year. The IPCC finding of a warming trend and thinner ice is accepted, but any use of this trend in planning of transportation and engineering activities must be considered in the light of year-to year variability, and, as noted, the possibility of old ice in the passageways. In brief, the IPCC trends are accepted, but interpretation in Arctic engineering design and marine operations is far from straightforward.

The variability of ice conditions is well known, and Wilson et al. note that a "*false sense of optimism*" might be generated regarding the future shipping in the Canadian Arctic. Old ice might be present at any time and present a hazard. Engineers must account for all relevant uncertainties in their planning. As a result, a conservative approach is advocated; in other words, as in other engineering designs of systems for the future, it is prudent to plan for the worst.

For example, the engineer is required to consider ice features in design that will prevail over the lifetime of a facility, or over some specified return period. If we know from recent surveys that the kinds of ice features described at the beginning of this section exist, then even though the facility may be used over the next say forty years, the design ice features are clearly dominated by what are seen today – even if future ice features may be less severe. Furthermore, uncertain trends which may lead to more severe conditions have to be accounted for, even if not proven. These trends include water level changes and potentially a more severe wave climate if ice cover is diminished.

Even trends in thickness reduction may not continue and therefore cannot benefit either design or future planned operations. Apparently, the thickness reduction in the Arctic Basin is strongly influenced by the increased export of ice through the Fram Strait. It is not clear if this will continue or even reverse. As noted earlier, the thickness of multi-year ice in the channels of the Arctic Islands appears not to have changed in the past 40 years. This does not support thickness reduction due to warming. That said, we do not dispute the predictions, except in the context of uncertainty and apparent anomalies.

Finally, based on our experience in other regions where ice completely disappears in the summer, even if this does occur in the Arctic, the winter ice regime at will continue to be a formidable obstacle and challenge. As earlier described we would expect to continue to have first year ridges up to 40m thick; possibly thicker because of increased ice motion and wind driven internal ice pressure. To use the term “ice free” for the Arctic basin, in the context of offshore engineering, is very misleading.

1.2.3 Permafrost and ice roads

The degradation of permafrost due to warming trends is mostly a land-based issue and therefore is not a topic for this study. Nevertheless, the issue has some relevance to the oceans as well.

In permafrost zones, foundations and winter roads are engineered to rest upon frozen ground and maintain that condition. Warming temperatures cause areas of discontinuous permafrost to move further north, with regions of thawing permafrost. The result is slumping of the ground, tilted trees, sinkholes, and related disturbances, along with declining viability of winter roads. This can have a significant impact on Northern communities and resource development projects that rely on winter roads. Typically, these roads are used beginning in November or December and are viable until March or April, but milder winters are disrupting this schedule. In cases where the only other option is airlift, this results in a significant increase in the cost of supplies. All-weather roads offer an alternative for future construction but are costly. The other alternative for coastal locations is to use marine access. Thus, permafrost degradation and a shorter season for ice roads places more emphasis on the importance of docks and harbours, as well as the marine systems themselves.

In addition to the problems for winter roads over permafrost, shorter winters and higher average temperatures will reduce the amount of time that near-shore ice roads (and river crossings) can safely be used, with a reduction in the length of the transportation window. This can mean significant losses for impacted industries and communities. Ice roads have become increasingly unreliable over the past few decades in certain parts of the North. Again, this may create the need for better access from water.

2 Canadian Activities and Engineering in Northern Oceans

2.1 Case Studies showing Canadian Experience

2.1.1 Introduction

Canadian industry and engineering specialists have made very significant contributions developing and applying knowledge about Northern issues with application to petroleum development and mineral resource extraction. There have been a number of Arctic projects, both Canadian and international, where Canadian engineering expertise played an important role. Highlights from some of them will be presented here, with more exhaustive information provided in Appendix B.

2.1.2 Overview of Canadian Project Experience

Developments in the Beaufort Sea starting in the late 1960s were the basis for much of the Arctic engineering capability that exists in Canada today. Three companies - Imperial Oil, Dome Petroleum and Gulf Canada Resources - created a significant body of expertise, demonstrating and safely implementing new methods for offshore operations in ice. Activities saw a progressive movement from on shore, to near shore in shallow water and eventually offshore to water up to about 70m deep. This incremental and progressive exposure to more severe ice environments facilitated a progressive improvement of Arctic engineering knowledge. Aspects included assessment of the Arctic ice environment, estimating likely extreme conditions, and prediction of ice forces for structure design. One of the means by which the petroleum industry collaborated to conduct the underlying research was through the Arctic Petroleum Operators Association (APOA). Over 200 projects were carried out under the auspices of APOA (see listing of projects in Appendix C) during the 1970s and early 1980s. Results were shared between supporting companies, but after 5 years, the reports were released to the public domain, and now can be accessed through the Arctic Institute of North America at the University of Calgary Library.

Platforms for offshore drilling evolved from dredged islands in up to 20m of water to caisson-retained bottom-founded structures and floating systems in deeper water; Figures 2.1 to 2.4 show examples of these platforms.

Figure 2.1: Dredged Island in the ice – used for exploratory drilling by Imperial Oil [Beaufort Sea, circa 1976] (Photo source unknown)

Figure 2.2: The Esso caisson-retained island [Beaufort Sea – 1985] (Photo: K R Croasdale & Associates Ltd.)

Figure 2.3: Gulf Canada's *Molikpaq* drilling caisson [Beaufort Sea, circa 1986] (Photo: G. Comfort)

Figure 2.4: The *Kulluk*: an ice-resistant round drillship developed by Gulf Canada [Beaufort Sea, circa 1985] (Photo: Brian Wright)

As each of these systems was deployed, ice monitoring systems were utilized to gather performance experience and refine design approaches. To gain confidence in moving to bottom-founded caisson systems for deeper water, field projects were conducted to gain insights into the ice forces from impact of massive and thick multi-year floes. One such initiative was at Hans Island, between Ellesmere Island and Greenland, where three field projects were conducted to measure the deceleration of massive ice floes, from which ice forces were estimated. The measurements demonstrated that the ice forces could be accommodated in structure design. Bottom-founded caisson systems such as such as Tarsiut Island, *Molikpaq*, the Caisson Retained Island and the Single Steel Drilling Caisson (SSDC - a modified and reinforced tanker) followed in the 1980s. They were instrumented to measure ice forces, structure response and soil foundation resistance, and consequently more valuable performance data were acquired. Floating drilling systems were also adapted for summer drilling in deeper water, using reinforced drill ships or the purpose-built *Kulluk*(conical drilling unit) which could operate into late autumn. The *Kulluk*was instrumented and provided unique data on ice forces on floating structures. With these floating drilling systems there was need for ice breaking supply boats and icebreakers. Vessels with innovative designs such as the *Kigoriak* and *Terry Fox* were brought into service, and the expertise of naval architects who designed them is still being sought.

In parallel with the activities in the Canadian Beaufort, commencing the 1970s considerable exploration drilling took place on the Grand Banks off Newfoundland. The first iceberg towing experiments were conducted in 1972 by Memorial University supported by Mobil, Imperial and Amoco. An East Coast Operators Association conducted joint research (similar to APOA) primarily to address iceberg management issues. C-CORE was formed in 1975 to undertake much of the required research within Memorial University. Hibernia was discovered in 1978.

Three oil fields are now in production on the east coast of Canada: Hibernia, Terra Nova and White Rose. The Hebron offshore platform (gravity-based) is under construction, and a wellhead platform tied back to the existing *SeaRose* Floating Production, Storage and Offloading vessel (FPSO) is being considered for the White Rose project. All of these developments have taken place in areas where sea ice and icebergs pose a challenge to the design of installations. Two strategies with regard to possible interaction with icebergs have been considered. The structures can be designed to resist iceberg loading: for example, gravity-based structures which generally cannot be moved from location. Significant effort is made to detect icebergs using radar and other means, and to remove threatening icebergs by towing. Floating structures, on the other hand, can be designed to disconnect if a threatening iceberg comes too close.

Again, iceberg detection, drift prediction and towing are used for management, followed by disconnect as a final remedy. Effective design for either strategy requires comprehensive information of the environment, wind, waves and ice, an assessment of the risk of ice impact and a definition of the corresponding ice forces. These demands have fostered a broad range of engineering expertise in Canada, which has been recognized and seen application in other countries.

Pack ice can be expected at the White Rose location every few years, for example with 5/10 coverage 1 out of 4 years. The average number of days when ice is present is 17, with an average thickness of 0.4 metres. The average number of icebergs in the degree square was taken as 0.95, averaged over the year. The derived length distribution is shown in Figure 2.5, with the ice management policy illustrated in Figure 2.6.

The *Terra Nova* and the *SeaRose* are examples of turret-moored disconnectible FPSOs. The strategy in this case is to plan disconnection and removal of the unit if an iceberg cannot be removed. There is also the situation that detection of icebergs can be less reliable in the presence of high sea states, and at the same time smaller icebergs will be accelerated by the wave action, with much increased velocity and consequently kinetic energy.

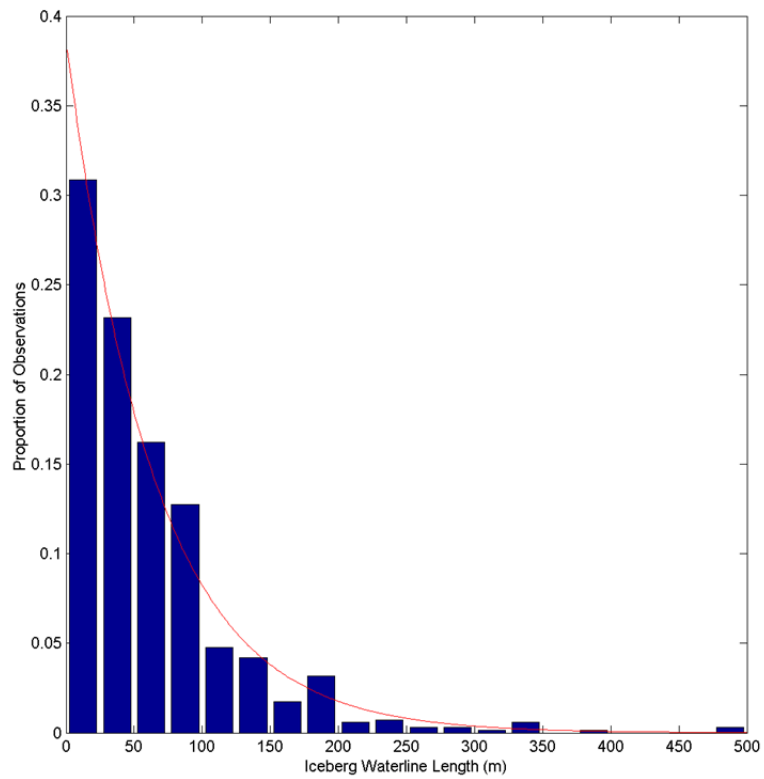

Figure 2.5: Iceberg length distribution (Jordaan *et al.*, 2014)

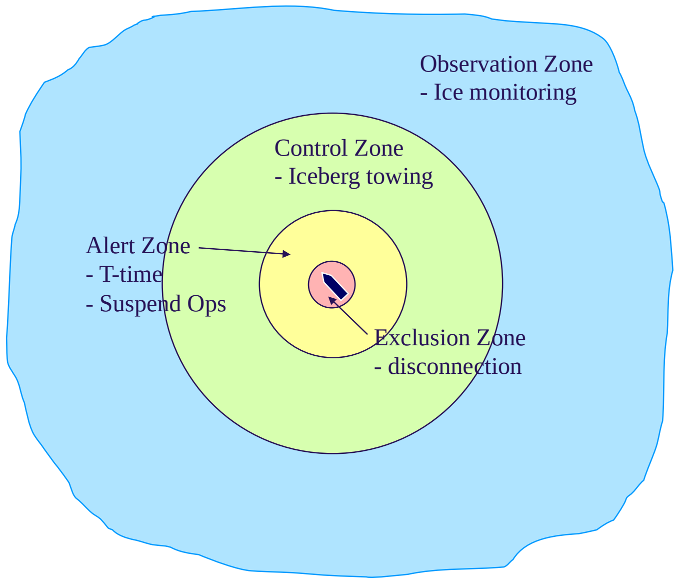

Figure 2.6: Strategic ice management (Jordaan *et al.*, 2014)

The situation described poses a complex situation for design and the solution was found by means of probabilistic analysis. Methods based on this approach have been pioneered in Canada, together with guidance on safety levels in CSA S471 (Canadian Standards Association Standard: General Requirements, Design Criteria, the Environment, and Loads) and ISO 19906:2010 (Petroleum and Natural Gas Industries—Arctic Offshore Structures). The analysis accounted for factors such as area density of icebergs, ice management, environmental conditions including sea state, and the mechanics of the interaction. Design was based on Safety Class 1 - failure would result in great risk to life or a high potential for environmental damage, for the loading condition under consideration with a Target Safety Level = 1 in 100,000 years or 10^{-5} per annum.

The final recommendations were made regarding local and global pressures from potential collisions with ice. These formed the basis of the design and selection of steel structure and plating. Design checks on structural response were also carried out by the team in St John's. The probabilistic methodology together with developments in the understanding of ice mechanics has led to much improved competitiveness of the designs, accounting for cost and safety.

Figure 2.7: The White Rose development showing the *SeaRose* vessel and tanker **(**http://www.offshoreenergytoday.com/canada-approves-amendment-to-huskys-white-rose-fdp/)

Figure 2.8: The *SeaRose* under construction [Marystown, NL, circa 2005] (Photo: Keiwit)

At about the same time as the petroleum exploration activities in the Beaufort Sea and off the East Coast, an active drilling program was being carried out in the Arctic Islands with the novel approach of using land rigs on thickened ice sheets to drill exploratory wells from the land-fast ice between the islands. Thirty-three such wells were successfully drilled. Engineering challenges included placing large loads on floating ice covers, assessing ice conditions to ensure stability of the ice, logistics of air transport of equipment, fuel, supplies and personnel, and operating under the extreme Arctic conditions of cold and darkness. The extensive gas finds from this program stimulated the Arctic Pilot Project to design and build a gas pipeline, a liquefaction plant, terminal and large icebreaking LNG carriers to move the gas to market. Advances in arctic marine technology were made relating to year round operation of the marine terminal and transit of the icebreaking LNG carriers. The basis for this was definition and forecasting of the ice environment to facilitate economic design and operation of the facilities and LNG carriers.

Two major mining projects, Nanisivik on Baffin Island and Polaris on Little Cornwallis Island, were undertaken in the 1970s and continued operating through to the early 2000s with seasonal shipping of concentrate. In both cases a mine, mill, staff accommodation and deep-water dock were designed, built and operated successfully in spite of the remote location. The MV *Arctic*, an icebreaking bulk carrier built in Canada, gained important experience on extended season shipping of concentrate from the mines. An important aspect of the Polaris project from a marine engineering point of view was the successful use of a sheet-piled dock in a channel where the dock was exposed to drifting thick winter ice. Mines typically have a finite life. The Polaris mine was designed and constructed to facilitate removal and easy reclamation of the site after closing. The whole mill was barge-mounted to facilitate removal. At Nanisivik, the deep-water dock has been left in place as a base for the Department of National Defence's Nanisivik Naval Facility.

A more recent project is the Voisey's Bay mine development on the Labrador coast. The mine started operation in 2005. It involves a nickel mine, concentrating mill, accommodation for staff, a deep-water loading facility and year-round shipping. The icebreaking bulk carrier, MV *Umiak* 1, was designed and built for this trade. Sea ice is present at the dock site and along the coast from December through to June. This established special requirements for the design of the wharf and bulk carrier, and accommodation of traditional use of the ice cover by local residents in winter. These engineering and local factors had to be addressed and reconciled. The ice cover in the winter is a convenient surface for travel by local residents. Shared use of the ice was achieved by communicating information on transits of the ship, use of moveable 'bridges' at certain points along the broken channel left in the ice, and closing of shipping for a selected period during the winter. This shared use of the ice cover is a good example of how constructive solutions can be found to combining development and local interests.

The Kashagan oil field in the North Caspian is the world's largest discovery in the past 30 years. The area is ice covered for 3–4 months each winter, and while much less severe than in the Arctic Ocean, nevertheless ice has significant effects on the design and operation of offshore platforms and pipelines. In 2001 a Canadian group was successful in winning a bid to collect ice data and develop ice design criteria for the project. The Canadian group continues its involvement in this project as it has gone from exploration, to delineation drilling and into development. Involvement in the project has exposed the Canadian team to new issues such as managing large ice rubble accumulations to prevent ice encroachment, and determining safe burial depths for these marine pipelines subject to ice interaction and damage. The approaches developed for Kashagan pipeline burial are considered state-of-the art and will now be available for use in other Arctic regions (including Canada) as developments occur.

The Shtokman Field in the Barents Sea is another project in which Canadian engineers played a significant role, using their expertise on iceberg load definition on floating structures. The probabilistic methods used in assessing iceberg loading on the Grand Banks, where two floating production platforms are now operating (the *Terra Nova* and *Sea Rose* FPSOs) were adapted for conditions in the Barents Sea. The Barents Sea experience has resulted in an improved methodology, which has raised interest in its use in other areas.

2.1.3 Conclusions from Case Studies

The pioneering work in petroleum exploration in the Beaufort Sea, the Grand Banks and Arctic Islands, and mine developments in the high Arctic provided the impetus for innovation in the design, construction and operation of structures and ships for the Arctic. These case studies demonstrate the progressive development of Arctic engineering in Canada and its recognition internationally. Participation in international projects produced direct benefits for Canadian engineers in terms of recognition and remuneration, but also provides new opportunities for extending knowledge, broadening international opportunities and bringing this new expertise home to Canada.

2.2 Canadian Contributions to Codes and Standards

As a northern country, Canada has developed a number of codes and standards that include portions addressing northern or cold regions issues, for example the National Building Code (NBC, 2010) and the CSA Canadian Highway Bridge Design Code (CSA, 2006). It was not until the 1970s and 1980s that codes directly related to operations and activities in northern oceans began to be developed. One of the first ones was in 1972, when the Canadian Government drafted the Arctic Shipping Pollution Prevention Regulations (ASPPR) to regulate navigation in Canadian waters north of 60ºN latitude. These regulations divided the Canadian Arctic into Shipping Safety Control Zones, established a number of Arctic Classes related to the thickness of level ice that could be broken, and provided a table that regulated when various ice class ships were allowed to enter each Control Zone. In 1989 the ASPPR were revised (ASPPR, 1989), reducing the number of ice classes, relating them more to the risk of damage, and introducing an Ice Regime system which related shipping access to actual ice conditions. Together, regulation for construction and operation of icebreaking ships was provided. These revisions were subsequently subject to an extensive review as well as a study of maximum bow force (Carter et al., 1992, 1996), and implemented in 1996 (ASPPR, 1996). Extensive expertise of Canadian naval architects and engineers was used in developing and reviewing these standards.

In parallel, in the 1970s offshore exploratory drilling for petroleum was initiated off the East Coast and in the Beaufort Sea. Developing offshore resources, often in hazardous environments, presented a challenge in meeting the goals of protecting human life and preserving environmental quality. Governmental regulatory authorities and the petroleum industry faced this challenge in the exploitation of offshore petroleum resources, and initiated a program by the Canadian Standards Association (CSA) in 1984 to develop a Canadian offshore structures code. The CSA Offshore Structures Code was developed during the late 1980s, and was subsequently adopted in the early 1990s. The Code comprises five standards: CAN/CSA-S471- 92 General Requirements, Design Criteria, the Environment, and Loads; CAN/CSA-S472-92 Foundations; CAN/CSA-S473-92 Steel Structures; S474-94 Concrete Structures; and S475-93 Sea Operations. These Standards have been used in Canada and elsewhere, particularly because of their treatment of extreme environments: i.e., sea ice, icebergs, and combinations of these with other environmental factors such as waves and earthquakes. These were the first offshore standards based on limit states and reliability, with target safety levels, load and resistance partial factors. Canadian engineering expertise was the foundation of these standards, which on publication were also used by operators outside Canada.

Already by the late 1990s it was apparent that harmonized international standards were needed, given the global nature of the marine and petroleum industries. This has led to Canadian engineers playing leading roles in the development of international standards. The International Organization for Standardization (ISO) already had underway an initiative to develop a suite of standards for offshore structures for the petroleum and natural gas industries. In 2000 an initiative was undertaken to develop an international standard for Arctic offshore structures. Canada provided the lead for this activity and the CSA offshore standards were a basis for significant parts of the ISO Arctic offshore standard. Many Canadian engineers participated in drafting the standard. The standard ISO 19906 Arctic Offshore Structures was published in 2010 and adopted as a National Standard of Canada in 2011 (CSA, 2011).

On the marine side a harmonization initiative was also being pursued. On the ship structure and ship machinery side, the International Association of Classification Societies (IACS) has harmonized their classifications for Arctic vessels and has developed standards for seven Polar Class (PC) vessels. A set of requirements for Polar Class vessels was first published in 2007, with an updated version in 2011 (IACS, 2011). Canadian naval architects and engineers contributed to the development of these unified requirements. On a broader basis, the International Maritime Organization (IMO) is developing a mandatory International Code of Safety for Ships Operating in Polar Waters. It will provide requirements for ship construction (parallel to IACS), equipment, operation (eg., ice forecasts, icebreaker assistance) and environmental protection; be applied not only to ice-covered waters, but to all polar waters (i.e. Arctic and Antarctic); allow only partially or totally enclosed lifeboats; set qualifications of ice navigators; and set high standards for environmental protection. It is expected to take effect in 2016. Canadian naval architects and engineers are contributing.

2.3 Canadian Expertise on Northern Engineering

2.3.1 Origins

Even before engineering was categorized as a formal topic, traditional knowledge of the Inuit incorporated intimate and sophisticated knowledge of snow and ice, enabling them to create a sustainable lifestyle in a very harsh environment.

The early European settlers also had to cope with more severe snow and ice than they had been used to. With the help of the established knowledge of the First Nations, they learned to live in a harsh winter environment. Empirical knowledge was developed to travel over ice and build harbours and bridges to withstand the ice.

Commencing in the late 19th and early 20th centuries, more formal studies based on science and engineering were initiated in order to better understand ice and to develop engineering guidelines to design for it.

For example, as early as 1898 records show that an incident of ice damage to a river bridge pier was reported and analyzed briefly in an article in the Transactions of the Canadian Society of Civil Engineers (Leonard, 1898). Of interest to ice engineers is that the 1898 case resulted in an estimate of the ice pressure causing the damage at 150 psi, about 1 MPa (Neill, 1974).

Professor Bernard Michel reviewed ice engineering history in Canada (Michel, 1981) and referred to the pioneering work of Professor H. T. Barnes of McGill University. In 1914, Professor Barnes was one of the first to perform crushing strength tests on ice. Michel quoted Barnes as saying: “Tests on the crushing strength of ice are of no value in themselves. The crushing strength depends on the rate of loading, and the time element is the greatest factor in determining the pressure of ice against a structure”. Barnes also discovered that there was a large difference in the results of testing columnar ice along the column axis as compared to perpendicular to it. He found an average crushing strength value of 363 psi (2.5 MPa) for St. Lawrence

River ice. It is believed that this is the origin of the 400 psi value used in Canadian bridge codes.

During the first part of the 20^{th} century, Canadian ice engineering focused mostly on designing bridges and harbour structures to resist ice, as well as developing reliable predictions for the weights of goods that could be transported across the ice. Ice roads were important to mining and logging operations, as well as for the supply of remote communities.

Centres of expertise gradually developed at the National Research Council in Ottawa and at some universities. It is of note that during the dark days of the 1939-45 war, the National Research Council coordinated effort across Canada to study the possibility of reinforced ice for floating ice airfields to defend the Atlantic convoys. Called the Habbakuk Project (see list of APOA reports, Appendix C), this was apparently given the blessing of Winston Churchill, who was appalled by the severe convoy losses and intrigued with the idea of using nature as an ally (originally the thought was to use tabular icebergs). The Canadians were given the job: research was performed on ice reinforced with wood pulp at universities across the country and ice beams were tested on frozen lakes. By the time the issues had been evaluated and understood, the U boat threat had been addressed by other means.

The case histories described earlier in this report have outlined how, commencing in about 1970, Canadians became leaders in developing methods for offshore drilling in the Beaufort Sea. It should be remembered that at its zenith in the late 1970s – early 1980s, oil and gas exploration in the Canadian Beaufort Sea was a considerable enterprise. It involved thousands of Canadians (many local Northerners), as well as new technology developed mostly in Canada. It is an important case-history, because it created a significant body of Canadian Arctic engineering expertise and demonstrated how new methods for offshore operations in ice were developed and safely implemented. Many of today's Canadian Arctic offshore engineers developed their skills in this first phase of Beaufort Sea exploration. At that time the Canadian oil companies were prominent in pushing the technology envelope.

Today most multi-national oil companies headquarter their Arctic R&D in their home countries; for American companies, the location is usually Houston. They do use Canadian expertise, but control it from their HQs. This is a reflection of how most large organizations generally like to centralize corporate functions such as R&D in one place and usually in their home nation. It also reflects the fact that in today's world, other Arctic regions in addition to Canada are in the multi-national's portfolio.

2.3.2 A Survey of Current Capabilities

In order to assess the current situation, the authors of this report conducted a brief survey on Arctic offshore expertise in Canada. Based on their own networks, known organizations and participants were asked to respond on numbers of Arctic engineering experts, geographic areas of activity etc. The results are summarized as follows:

- The survey indicates a total of about 120 Canadian Arctic engineering experts are currently active.
- Geographically they are distributed as follows:
    - Vancouver and the island – 16
    - Calgary – 42
    - Ottawa -20
    - St John’s – 37
    - Other Canadian and international – 9
- By organization:
    - Oil Companies – 20
    - Large Consulting Companies – 11
    - Small Consulting Companies (many as individuals) – 31
    - Universities - 7
    - Institutes – 25
    - Government - 32

Geographic areas of involvement include Canada, USA (Alaska), Russia (Arctic and Far East), Kazakhstan (Caspian Sea), Greenland, the Baltic and Barents Sea.

Clients are based in the above regions but also in countries involved in activities in those geographic areas. These include oil and engineering companies based in Britain, France, Singapore, Japan, Germany, Norway, Finland and The Netherlands.

The range of typical activities conducted by Canadian experts for the above clients and in the above regions includes:

- R&D into the fundamentals of ice mechanics
- Ice–structure and ice–ship interactions
- Ice detection and ice management
- On-ice field work to measure ice morphology and strength
- Ice characterization and forecasting – usually based on satellite imagery analysis
- Development of statistical descriptions of the ice environment
- Ice motion modelling and its application to environmental issues such as oil spills
- Development of ice design criteria, especially ice loads on platforms and ice resistance of ships
- Platform designs for ice-covered waters

- Logistics and operations in ice-covered waters including escape and evacuation
- Ice model tank experiments to aid in the above topics
- Ice roads and ice platforms
- Ice design criteria for offshore pipelines, especially burial depths to avoid ice gouging of the sea floor
- Training on ice topics, including courses to industry personnel
- Leadership and contributions to development of International Codes and Standards

It should also be noted that the contributions of Canadian experts are often hidden within larger project activities by either major oil companies or large EPC contractors. These organizations often seek out Canadian experts (even in preference to domestic experts within the country of activity); in our opinion this is a reflection of the high level of competence achieved by Canadian experts.

The survey did not attempt to put a precise value on this work, but direct annual revenues by these specialists and their organizations are estimated to be between 20 and 30 million dollars. Much of this can be classed as R&D, and is certainly leading edge, and much is supported by foreign income.

One of the ongoing issues for Arctic Engineering is sustainability of expertise. As discussed, many experts developed their skills commencing with the surge of activity in the Canadian Beaufort Sea and the Grand Banks in the 1970s and 1980s. Most are close to or beyond retirement age. Few universities specialize in Arctic offshore topics; in fact currently only Memorial University has a sustained program. Over the past decade the number of universities conducting Arctic engineering research and training has decreased.

Despite the downturn in Canadian Arctic activities due to various factors including oil prices and small discoveries, a critical mass of expertise survived and has prospered to the extent that it is recognized and sought after world-wide. Canadian projects such as East Coast oil development and the Confederation Bridge were helpful in sustaining the expertise and involving younger Canadian engineers, but it would have shrunk considerably had not Canadians been able to successfully compete internationally, as demonstrated in the case histories reported in this study. The enthusiasm and vision for Canada's North which prevailed in the 1970s did lead to the expansion of National Research Council (NRC) Arctic activities and to the establishment of centres of expertise such as C-CORE. These can play a vital future role. As younger engineers enter the field, it is the responsibility of experienced engineers to provide mentorship to meet the challenges of sustaining and enhancing future Canadian expertise. Going forward, the minimal involvement of First Nations in work to date also needs to be addressed.

2.4 Inventory of Canadian Centres Oriented towards Northern Research

In addition to the survey of individual expertise, an inventory of agencies conducting or supporting R&D related to Canada's Northern Oceans has been conducted using the project team's knowledge and contacts. Most current and recent research is well documented and searchable on the internet. There is an extensive body of older and still relevant research that is not accessible over the internet. The following provides a summary statement; complete details are found in Appendix D.

2.4.1 ArcticNet

ArcticNet is a Network of Centres of Excellence of Canada that brings together scientists and managers in the natural, human health and social sciences with their partners from Inuit organizations, Northern communities, federal and provincial agencies and the private sector. Under the leadership of Université Laval and University of Manitoba, universities and agencies from across Canada are engaged in a variety of projects in the areas of the impact of climate change and modernization. The projects are largely science oriented but can provide useful background information for engineering applications.

2.4.2 Centre for the North (CFN)

The Centre for the North is an initiative of the Conference Board of Canada. The goal is to bring Aboriginal leaders, businesses, governments, and community advocates together to identify challenges and opportunities, and to decide how those challenges can be met. They have completed a number of relevant reports, in particular a recent one on economic development in Canada's northern marine waters. In addition it is potentially a good forum for dialogue with Northerners.

2.4.3 Canadian Polar Commission (Government of Canada)

The Canadian Polar Commission has responsibility for: monitoring, promoting and disseminating knowledge of the polar regions; contributing to public awareness of the importance of polar science to Canada; enhancing Canada's international profile as a circumpolar nation; and recommending polar science policy direction to government. It is a valuable source of background information for engineering studies.

2.4.4 Canadian High Arctic Research Station (CHARS)

The Canadian High Arctic Research Station (CHARS) will provide a world-class hub for science and technology in Canada's North that complements and anchors the network of smaller regional facilities across the North. The new station will provide a suite of services for science and technology in Canada's North including a technology development centre, traditional knowledge centre, and advanced laboratories. CHARS is located in Cambridge Bay, Nunavut. Its present focus is rather broad. The research program being developed is science oriented, with a place for engineering application. CHARS represents a potential location for a Northern educational institution.

2.4.5 C-CORE, LOOKNorth & CARD (centres within C-CORE)

C-CORE addresses challenges facing oil and gas development offshore Newfoundland and Labrador and other ice-prone regions. C-CORE is a multi-disciplinary organization with world-leading capability in Remote Sensing, Ice Engineering and Geotechnical Engineering. Headquartered in St John's NL, C-CORE maintains a close collaborative relationship with Memorial University. C-CORE is also home to LOOKNorth, a Canadian Centre of Excellence for remote sensing innovation to support northern resource development, and the Centre for Arctic Resource Development (CARD), an initiative in collaboration with industry, focusing on medium- to long-term Arctic research and development. C-CORE is a strong engineering consultancy with an extensive knowledge base.

2.4.6 Canadian Network of Northern Research Operators

The Canadian Network of Northern Research Operators (CNNRO) facilitates collaboration and the exchange of information among all stakeholders who share an interest in infrastructure and logistics to support research in Northern Canada. Potentially could assist in providing logistic support for field work.

2.4.7 Arctic Institute of North America (at University of Calgary)

The Arctic Institute of North America is a multi-disciplinary research institute of the University of Calgary. The institute's mandate is to advance the study of the North American and circumpolar Arctic through the natural and social sciences, the arts and humanities and to acquire, preserve and disseminate information on physical, environmental and social conditions in the North. It is a great store of documents and studies focused on environmental, social science and engineering issues.

2.4.8 NRC Arctic Program

This research program includes thrusts on resource development, northern transportation, marine safety technology and community infrastructure. NRC has a long history of northern engineering research extending back over 60 years and is a strong repository of Arctic engineering knowledge and expertise.

2.4.9 Program of Energy Research and Development (PERD)

The Program of Energy Research and Development (PERD) is a federal, interdepartmental program operated by Natural Resources Canada (NRCan). PERD funds research and development designed to ensure a sustainable energy future for Canada in the best interests of both our economy and our environment. It includes programs on offshore environmental factors, northern regulations, marine transportation and environmental impacts. Results of projects contribute engineering knowledge of Arctic offshore.

2.4.10 Polar Continental Shelf Program (PCSP)

The PCSP coordinates field logistics in support of advancing scientific knowledge and management of Canada's lands and natural resources. As a national service delivery organization, PCSP coordinates logistics for federal, provincial and territorial government agencies, northern organizations, universities and independent groups conducting research in Canada's North. The program provides good logistics support to engineering research field work.

2.4.11 Beaufort Regional Environment Assessment (BREA) 2011-14

BREA is a four year (2011 to 2015) multi-stakeholder initiative that is sponsoring regional environmental and socio-economic research to assist in preparing all parties, including the federal government and local communities, to respond to new investments in oil and gas in the Beaufort Sea. Results of some projects have engineering application.

2.4.12 Environmental Studies Research Funds (ESRF), CAPP supported

ESRF is a research program which sponsors environmental and social studies. It is designed to assist in the decision-making process related to oil and gas exploration and development on Canada's frontier lands. The ESRF is directed by a joint government/industry/public Management Board. Results of many projects have engineering application.

2.4.13 Canadian International Centre for the Arctic Region

As part of Canada's Arctic foreign policy, a dedicated Canadian International Centre for the Arctic Region (CICAR) was established in 2009. CICAR is located in the Canadian Embassy in Oslo, Norway and has a network of officers at Canada's embassies in North America, Europe and Asia. This Centre could provide linkages between Canadian engineers and international partners.

2.4.14 Industry and Consultants

The survey summarized in Section 2.3.2 indicated that of the approximately 120 Arctic offshore engineers currently active, about half (60) are working within industry or as consultants. There about 20 employed (or under contract) full time in the oil industry.

Most of these are associated with the Chevron Arctic Centre, which currently is the only dedicated oil industry Arctic group in Canada. To quote from the Chevron website *"it is home to some of the world's foremost experts in Arctic exploration and development. The Center consists of a core group of Arctic subject matter experts who support Arctic exploration, asset development and business development projects across the Chevron global upstream. The group has expertise in the following disciplines:*

- *Regulatory & Policy*
- *Environment*
- *Seismic*
- *Drilling*
- *Facilities*
- *Ice Engineering*
- *Structures*
- *Marine*
- *Naval Architecture*
- *Logistics*
- *Development"*

Other major oil companies with Arctic interests have similar groups, but are located mostly in the USA. Often, they will use Canadian consultants to bolster their work; in fact, many Canadian Arctic engineering specialists spend the majority of their time working for such foreign entities.

Some of the larger global EDC contractors also employ Arctic engineers in their Canadian offices. Our survey indicated about 10 Arctic specialists employed by this category. Companies include Ausenco (who had previously bought out Sandwell - who had previously acquired Swan Wooster) and Worley Parsons.

Other Canadian consultants (about 30 in our survey) tend to be individuals or those employed by small consulting entities or small specialists group within larger Canadian consulting companies. Individuals are not named here, but small/specialized companies include: AKAC; Canatec Consultants; Golder Associates; BMT Fleet Technology; Tetra Tech EBA and Bercha Associates.

2.5 Review of Recent Reports

Many of the organizations listed in Section 2.4 conduct focused reviews of northern issues and produce reports. In conducting this study, relevant recent reports have been reviewed. They provide useful background and specialized inputs and perspectives. This review was also thought necessary to avoid duplication. A summary is provided here to indicate their scope, and key conclusions where appropriate. Those most relevant to this study are given more space. The full review is provided in Appendix E.

2.5.1 Centre for the North (CFN) *Changing Tides*: Economic Development in Canada's Northern Marine Waters (Fournier, S. and Caron-Vuotari, M., 2013)

The report emphasizes that Canada's northern marine waters represent one of the world's last natural resource frontiers. Development will hinge on four factors: climate change, infrastructure, emergency response and search-and-rescue (SAR), and commodity prices. It summarizes renewed interest in oil and gas exploration in the Beaufort Sea, and recent offshore licenses in deeper waters in Beaufort Sea.

The report discusses climate change and its possible effects on access both marine and overland. It emphasizes that the only deepwater port in the Arctic at present is at Churchill, Manitoba. One is planned by the Canadian government for Nanisivik, Nunavut, expanding the facility developed for the Nanisivik mine. SAR facilities and disaster response capability are seen to be inadequate.

Development of industry and commercial enterprises can be a driver for the development of facilities. A boom-and-bust issue is associated with this: facilities can be built for a particular development, used, and then not retained (or not be suitable) for community use.

The report gives examples of approved and plausible projects in Canada's North, those relating to the oceans include:

- a Government of Canada investment in a refuelling and docking station for military and coastguard vessels (although originally intended as a more expansive deepwater port facility) at Nanisivik;

- a possible private sector investment in a deepwater port and road at the head of Bathurst Inlet, Nunavut for mining operations (zinc and gold) in the region; and

- a potential expanded role for the Port of Churchill through the provision of services to communities and mining operations along the Kivalliq coast and in meeting freight demands for Nunavut in general.

The report comments on the need for collaboration in decision making and governance; leveraging of private and public sector resources; addressing uncertainties; risk management; and that *"The way that the risks and benefits of economic development are weighted and managed must make sense to Northerners, keep their interests front and centre, and effectively capture the Northern context."*

2.5.2 CFN Northern Assets: Transportation Infrastructure in Remote Communities (Bristow, M. and Gill, V., 2011)

A general point is made that transportation infrastructure in northern communities is significantly more expensive to develop than in the south. Transportation infrastructure in Canada's North is sparse.

Again, the effects of climate change are discussed, with its effects on roads and access.

Marine transport offers the least expensive transportation method for freight and is used for transporting fuel, groceries and other commercial freight to the Northwest Territories, Nunavut, and the northern regions of provinces with tidewater access. At the same time, there is very little marine infrastructure in the North, and almost none in Nunavut. Cargo is often offloaded onto beaches, and access to these landing sites can be unpredictable. The marine shipping season is short, ranging from one to five months, depending on the location of the community.

The report considers a case study of Churchill, Manitoba. This port is not connected to the road system in northern Manitoba, but has access to air, rail and marine transportation, air and rail being available year-round. Churchill is also the home to the only operating deepwater port in the Arctic region, making it a possible shipping hub for the far North. A number of key issues in the Churchill case study provided background for development in other northern communities.

2.5.3 CFN Future of Mining

The results of the study suggest key areas for policy recommendations to support future sustainable mining development in Canada's North:

- a competitive business environment for the mining industry;
- addressing infrastructure gaps and needs;
- recruitment initiatives aimed at women, new Canadians, youth and Aboriginal workers;
- meaningful community consultations and ensuring the implementation of Aboriginal land claims and resource development agreements;
- improving regulatory processes and personnel turnover in government regulatory bodies; and
- further investments in geoscience.

This report is reviewed in detail in Appendix E.

2.5.4 CCA Northern Ocean Science in Canada: Meeting the Challenge, Seizing the Opportunity

Recognizing the importance of ocean science, the Canadian Consortium of Ocean Research Universities (CCORU) asked the Council of Canadian Academies (CCA) to undertake an assessment of the state of ocean science in Canada. The report was carried out by an expert panel formed by the Council of Canadian Academies (Council of Canadian Academies, 2013).

Canada's existing research capacity was investigated. The state of Canada's ageing research fleet was noted. Canada's output of ocean science was considered to be in the top rank at present, but at risk. Funding opportunities, for instance those offered by the Canada Foundation for Innovation, are enabling the establishment and management of large-scale infrastructure. This includes vessels and observation networks. Consortia such as CCORU, are emerging. These networks and alignments have resulted in several innovative, world-leading initiatives. Despite these advances, the Panel identified the gaps in the coordination and alignment of the ocean science community in Canada. These principally relate to lack of a national vision for ocean science and lack of effective national-level mechanisms to co-ordinate resources and sharing of infrastructure and knowledge among ocean scientists.

2.5.5 True North: Adapting Infrastructure to Climate Change in Northern Canada

This report was carried out by the National Round Table on the Environment and the Economy (2009).

By means of research and extensive consultation with stakeholders, the risks to northern infrastructure posed by climate change were investigated, along with opportunities for adaptation. The recommendations were primarily addressed to government and were focused on adaptation to climate change and the use of current and future policy and decision-making processes to this end. Building northern capacity to adapt to climate change was a prime motivation.

2.5.6 Arctic Marine Shipping Assessment (AMSA) 2009 (Arctic Council)

The Arctic Council in 2004 commissioned a working group to prepare the subject report. The report deals with climate change, Arctic marine transport, governance of Arctic shipping, current marine use, future scenarios, human and environmental considerations, and infrastructure. Natural resource development (hydrocarbons, hard minerals and fisheries) and regional trade were seen as the key drivers of future Arctic marine activity. A lack of major ports, except for those in northern Norway and northwest Russia, and other critical infrastructure poses significant difficulties for future Arctic marine operations. Destinational shipping is emphasized. Many Arctic residents depend on marine resources for subsistence and it is suggested that constructive and early engagement of local residents in planned Arctic marine development projects will be beneficial to their well-being.

The report is commendable in terms of the range and thoroughness of its coverage. Recommendations were made on Arctic marine safety, protection of Arctic people and the environment, and building Arctic marine infrastructure. Of particular interest are that the Arctic states should support the development and implementation of a comprehensive, multi-national Arctic SAR instrument, and that the Arctic states should cooperate in the development of Arctic marine infrastructure.

2.5.7 From Impacts to Adaptation: Canada in a Changing Climate 2007

This report was sponsored by Natural Resources Canada and Environment Canada (Lemmen et al., 2008). Its focus is on changing climate and adaptation to this change. The report points out that adaptive capacity in Canada is high, but that resource-dependent and Aboriginal communities are particularly vulnerable to climate changes. This vulnerability is magnified in the Arctic.

2.5.8 The Past is Always Present: Review of Offshore Drilling in the Canadian Arctic (National Energy Board, 2011)

The same-season relief well issue is covered. Regarding this matter, NEB affirmed its intent to retain its same-season relief well policy. The report also included the statement that "an applicant wishing to depart from our policy would have to demonstrate how they would meet or exceed the intended outcome of our policy. It would be up to us to determine, on a case-by-case basis, which tools are appropriate.... We acknowledge that there is a continual evolution of technology worldwide, including the technology needed to kill an out-of-control well. We are open to changing and evolving technology."

2.5.9 CARD Arctic Development Roadmap (CARD, 2012)

The report is focused on the oil and gas industries. As part of its planning process, the Centre for Arctic Resource Development (CARD) developed the "Arctic Development Roadmap" (CARD, 2012). The importance of this document for the present CAE study is that, in order to develop the roadmap, a series of interviews were conducted with the major oil and gas operators and consultants in order to get their perspectives. The oil and gas operators who were interviewed included ExxonMobil, Suncor, Husky Energy, Statoil, Chevron, Imperial Oil, Shell and ConocoPhillips. Appendix F lists past planning studies of relevance to the Canadian Arctic.

3 Future Opportunities and Challenges

3.1 Overview

Future opportunities for Canada in its Northern Oceans are varied and challenging. Examples include: development of mineral resources; increased tourism; new fisheries; creation of protected areas; improvements in northern settlements and the lives of Northerners; enhanced marine systems (both year-round shipping and ports) to support these activities; and enhancing sovereignty.

There are issues relating to the above which are broader than engineering, yet the engineering to support and enable future opportunities will be crucial, and this will be our focus.

3.2 Inventory of Mineral Resources

A first step in development of resources is to know what is there. The known and potential energy and mineral resources of the North are extensive. It is a vast and remote area, covering about 40% of Canada's land area plus significant offshore areas, and still only partially explored. Some of the natural resources of the North have been identified and a subset of them has been or is being exploited, but undoubtedly many remain to be discovered. Energy and mineral resources for the purpose of this review include hydrocarbons, metals and other minerals. Hydrocarbons are generally in liquid or gaseous form, but can also include solids – coal, for example. Petroleum and natural gas are found both onshore and offshore, and currently, while the offshore is attracting the most interest, there is ongoing exploration and production of oil and gas from onshore areas. Minerals include base metals such as iron, copper, zinc, nickel and other ores, precious metals such as gold and diamonds, and other minerals such as 'rare earths'. Some of these resources have been known for some time; Norman Wells oil and Yellowknife gold have long production histories, and the Mary River iron ore deposit has been known for over 50 years.

Identifying potential resource deposits involves both government and industry efforts. There is an ongoing program within the Government of Canada for geological mapping of energy and mineral resources in the North[1]. The knowledge from this program will advance geological knowledge in the North to support increased exploration of natural resources and inform decisions on land use that balance conservation and responsible resource development. Seismic surveys conducted by industry, offshore and onshore are aimed at identifying prospective hydrocarbon deposits.

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[1] https://www.nrcan.gc.ca/earth-sciences/resources/federal-programs/geomapping-energy-minerals/10904

See Appendix I for Minerals Map.

3.2.1 Hydrocarbons

According to the National Energy Board, approximately 35% of Canada's remaining marketable resources of natural gas and 37% of remaining recoverable light crude oil is in northern Canada (Canada's Energy Futures, 2011). These percentages reflect conventional oil and gas resources only and are exclusive of unconventional resources. (AANDC, 2013)

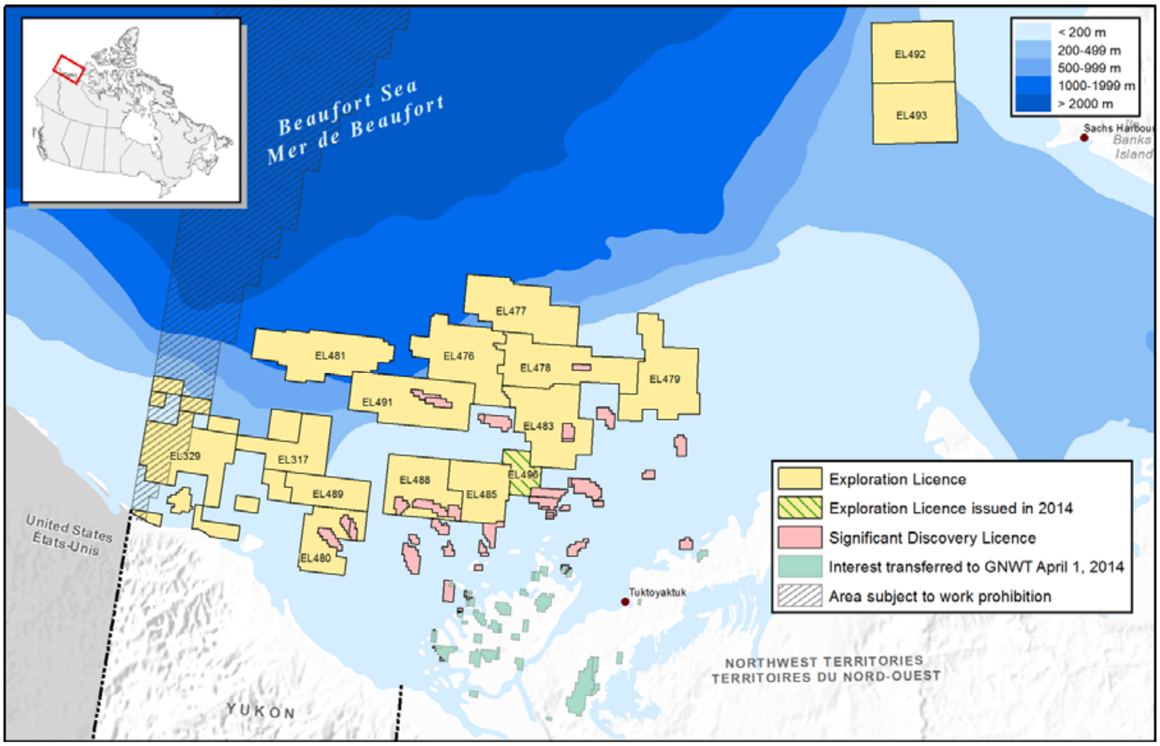

Figure 3.1: Beaufort Sea Leases (AANDC, 2014)

Regional estimates of Canada's northern discovered resources are listed in Appendix G. The totals for conventional oil and gas resources in discovered fields is 1.2 billion barrels of oil and 30 trillion cubic feet (TCF) of gas, and do not include estimates of potential in undrilled prospects and basins. Ultimate potential (which includes discovered resources and undiscovered potential) is estimated at about 12 billion barrels of oil recoverable and 150 TCF of gas, but much uncertainty remains about the resource potential in many of Canada's northern petroleum basins, especially those which have yet to be tested.

Recent studies indicate that an upwards revision of estimates of ultimate potential may be warranted. For example, a review of new information by the Geological Survey of Canada suggests that undiscovered resources in the Beaufort Sea – Mackenzie Delta Basin could more than double when extensive deep water potential is included. Thus the discovered resources only represent a small fraction of the potential.

Unconventional hydrocarbons are attracting oil and gas industry attention in the Mackenzie Valley. These potential resources include shale gas and shale oil in source rock known to have generated the oil at Norman Wells. These unconventional resources in the Mackenzie Valley have not been included in the potential, but make a significant addition.

3.2.2 Minerals

The mineral resources of the North represent a significant potential for economic development over the next decade (CFN, 2013). Historically, precious metals have been a driver, from the Yukon gold rush at the end of the 19th century to the gold mining in Yellowknife. Later, strategic minerals like radium and uranium were mined at Port Radium. The Geological Survey of Canada has over the years provided geological information which has greatly aided mineral exploration. Going from this general geological information to mineral prospects, discoveries, projects and eventually production is a long chain. The start of the process, prospecting is akin to finding a needle in a haystack. Thousands of potential sites are subject to surface surveys, prospecting, sampling and assessing before even a claim can be made. Surface shows need further evaluation to see if they are prospects that could eventually be projects. In 2012 almost half a billion dollars was spent on exploration in the North (CMA, 2013, Facts and Figures). There is a great winnowing-down process to what eventually may become a producing mine.

Currently there are a small number of actual producing mines in the North. To number some of them: there is one producing gold mine in Nunavut, three producing diamond mines in the Northwest Territories and two precious metal mines in the Yukon. The total value of mineral production in the North is now about 3 billion dollars; almost a 3 fold increase over the last decade. This is almost 10% of the value of the total mineral production for Canada. The values for the Northwest Territories, Nunavut and Yukon are $1.7, $0.6 and $0.5 billion, respectively, representing significant contributions to economic activity in the North. For each of these producing developments there are many more projects under development. For example, there are approximately 10 projects under development in each of Nunavut and the Northwest Territories. A listing of these for Nunavut and the Northwest Territories is included in Appendix H. Mining operations are a significant employer. The Meadowbank Gold Mine in Nunavut employs about 450 people. Total potential mining employment in Nunavut could reach 5000. In the Northwest Territories, with a more mature mining industry, employment stands at about 3000 with about another 2000 associated with developing projects.

3.2.3 Constraints

It should be remembered all mines and hydrocarbon developments have a finite life. For example, the Cominco lead-zinc mine at Little Cornwallis had a life of about 20 years and the lead-zinc mine at Nanisivik, 25 years. Both mines are closed and the sites have been reclaimed. This finite life has an impact on the infrastructure developed for the project, where decommissioning is also expected.

While there is great potential for resource development, there are many factors that determine whether a resource can be developed:

- world price for commodity,
- access to transportation,
- logistics support,
- environmental impact assessment,
- local socio-economic factors (local acceptance),
- availability of skilled workforce, and
- availability of financing.

Thus, identifying the presence of a resource is just a small part of the chain towards possible development. Engineering and technology can positively influence some of these factors.

3.3 Development Scenarios and Challenges

3.3.1 Hydrocarbons

The primary driver for oil and gas development is the presence of oil and gas in sufficient quantities to be economic. If the geology of an area is considered appropriate, geophysical surveys identify potential "structures" in which hydrocarbons may be present. These have to be drilled into to confirm hydrocarbon presence (or otherwise). Based on the results of this process in the past few decades, there are known deposits of oil and gas in Canada's Arctic offshore which as yet are undeveloped. In other areas, geological assessments and some geophysical work are underway but drilling has not yet occurred. Therefore, we can divide futures scenarios into two categories:

1. Where prior drilling has occurred and significant discoveries have been identified, but no development has yet occurred.

2. Areas with promising geology, but no exploratory drilling has yet been done.

3.3.1.1 Development of existing discoveries

Significant hydrocarbon discoveries exist in the Beaufort Sea, offshore Labrador and in the Arctic Archipelago. In the Beaufort Sea, as a result of the drilling in the period 1970 to 1992, the total of all significant discoveries is about 1.2 billion barrels of oil and about 10 TCF of natural gas. The largest deposit is Amauligak, in about 30m of water. It contains about 300 million barrels of recoverable oil. A field this size in other parts of the world with existing infrastructure and no ice would likely have already been developed. For Amauligak to be developed, a transportation system for the products is key. This could be a pipeline south or the use of icebreaking tankers. Either system would potentially create an infrastructure that would enable other smaller fields in the Canadian Beaufort also to be developed, as well as future discoveries.

Another region with significant discoveries is offshore Labrador. In this case, natural gas discoveries total 4.2 TCF. The water depths of the discoveries are 100m and deeper. The key challenges are that natural gas prices have been low and other lower-cost sources of natural gas are available. If natural gas rises in price (to, say, the oil price equivalent per British thermal unit (BTU), the motivation to develop could be created. Then, the technical challenges relate to icebergs and sea ice – in particular, platform design to resist more frequent icebergs than on the Grand Banks, and pipeline design and installation to get the gas to shore or to incorporate a floating LNG plant. This scenario is identified in the CARD Arctic Development Roadmap (Section 2.5.9).

Natural gas was discovered by Panarctic Oil in the Canadian Arctic Islands in the 1970s. The Hecla and Drake fields are on Melville and King Christian Islands and the waters offshore. The fields have an estimated 5.7 TCF of proven and 20 TCF of probable recoverable reserves. In 1978 an experimental gas pipeline was laid between the Drake F-76 wellhead in 55m of water and the shore of Melville Island, a distance of 1100m. The Arctic Pilot project in the early 1980s investigated the possibility of an LNG facility on Melville Island with ice-breaking LNG tankers taking the product to Europe. This is still a possible future scenario, but currently there are cheaper sources of natural gas around the world. The key technological challenge relates to building and operating an LNG plant in the High Arctic and then the design and operation of ice breaking LNG tankers.

There are also oil discoveries in the Canadian Arctic Islands: Bent Horn N-72 on Cameron Island and Cisco, offshore near Lougheed Island. The Bent Horn field is small, at 16 million barrels, but was the site of seasonal commercial production with about 3 million barrels being shipped south by the MV Arctic between 1985 and 1996. Cisco is a much larger field at about 600 million barrels, but being offshore in the Canadian Arctic Archipelago, it is unlikely to be developed with present technology.

3.3.1.2 Scenarios for future discoveries in ice-covered regions

The main interest of the present study lies in future oil and gas scenarios for Canada's Arctic (including ice-covered sub-Arctic regions). World-wide developments are of less importance but have some relevance in terms of the need (and opportunities) for Canadian services and products. In addition, technology developed for other Arctic regions may have application in Canada. Finally, any developments in the Arctic offshore in other jurisdictions may affect Canada's Arctic (e.g., transportation routes and potential environmental effects). Therefore, in the listing of scenarios for development of future discoveries it is useful to include both Canada and the rest of the world, but to keep them separate. The lists are as follows.

For Canada:

- Beaufort Sea (deeper water than prior discoveries mentioned above)
- The East Coast (generally further north than current production operations on the Grand Banks)
- Gulf of St Lawrence

Worldwide:

- Kara Sea, Laptev Sea, Russia
- US Beaufort Sea
- Chukchi Sea
- Offshore Greenland
- Barents Sea, Russia
- Sea of Okhotsk (Further north and in deeper water than current Sakhalin developments)

It is of interest to look at qualitative degrees of difficulty associated with a range of world-wide Arctic developments which include some of the above. This was included in the Arctic Development Roadmap (based on Scott, 2009) and is shown here as Figure 3.2, which is a rough guide; water depth in each region is also a major factor.

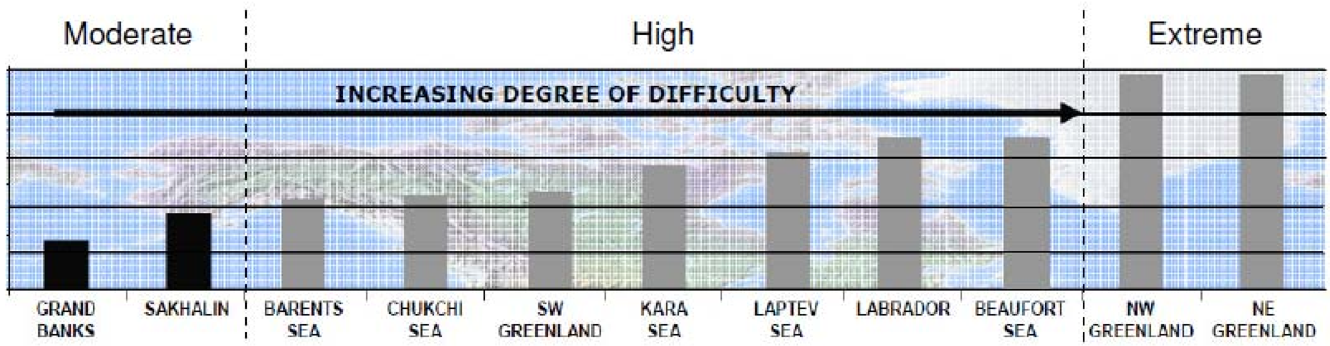

Figure 3.2: Relative degree of difficulty of various Arctic oil and gas development scenarios (CARD, 2012)

3.3.1.3 Issues identified relating to future Arctic oil and gas scenarios

No future oil and gas developments will take place in the Arctic unless they are economic, and should only take place with low risks to people and the environment. These criteria will be applied formally by the proponents and the regulators and perhaps less formally, but no less strongly, by society in general.

In their survey of the industry and the regulators, CARD in their Arctic Roadmap summarized and prioritized the key issues identified. It is useful to review these results before proceeding further. Figure 3.3 shows the issues/topic areas represented as a pyramid with the most critical at the top.

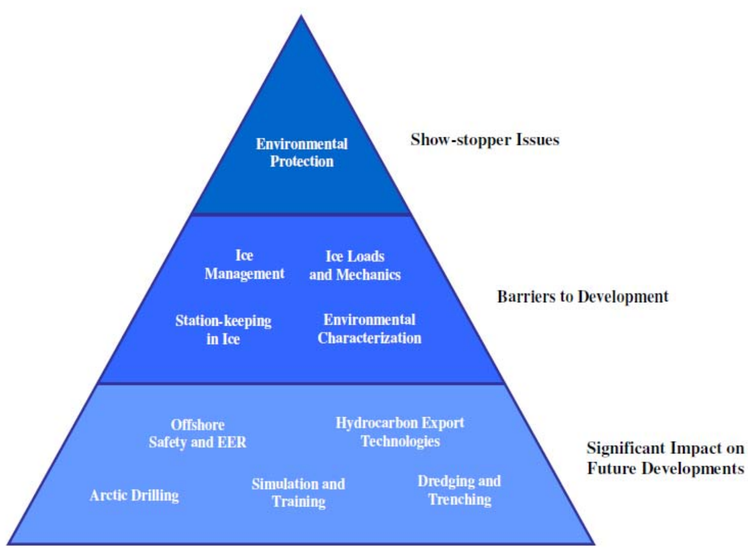

Figure 3.3: Extract from the CARD Arctic Development Roadmap study on key topics for Arctic offshore R&D for oil and gas production (CARD, 2012)

We now summarize the topics noted, followed by a discussion.

1. Environmental Protection: Regulatory approval is needed, together with emergency planning (in particular for oil spill prevention and response). Drilling of a same-season relief well poses difficulties as operations move further north, with shorter drilling seasons and more difficult ice conditions.

2. Ice Management: Management of ice is necessary for operations to deal with heavy ice conditions, and to extend drilling seasons. Forecasting of ice and metocean conditions is an important component in these operations, including such factors as sudden changes in the direction of ice movement.

3. Ice Mechanics and Loading: Local and global ice pressures are needed for design. The scale effect is most important in global design and would benefit significantly from more full-scale testing. Improved information on forces in pack ice is seen as a research need, as well as the mechanics of interaction of sloping structures with MY ice.

4. Station-keeping in Ice: This was seen as a need to extend drilling seasons. Control of offsets during drilling operations is an important factor. Improved mooring and dynamic positioning systems were seen as design needs.

5. Environmental Characterization: There is a need for improved information on ice and metocean conditions for real-time operations and for design. In the latter case, statistics on ice occurrence, types and thicknesses are needed. Improved forecasting of Arctic ice conditions and weather were seen as a further need.

Although the research directions suggested above are sensible and necessary for operations during part of the year, consideration must also be given to long-term development and production. The concept that a floating system be disconnected in given ice conditions is quite feasible if based on a clear condition – for example, the presence of an iceberg. In the High Arctic, with multi-year ice of varying thickness, including ridges, and possible changes of drift direction, the criteria for disconnection become difficult to define and operate. Year-round floating production as on the Grand Banks will be a considerable challenge for the Beaufort or Labrador Seas. Subsea installations, with pipelines to shallower water with less severe ice, may be a more robust approach. Nevertheless, floating systems with ice tolerance combined with ice management will still be needed for drilling, well servicing and contingencies such as relief-well drilling.

3.3.1.4 Hydrocarbons - Discussion

As has been noted already, a key driver of development is economics. Developments have to deliver value for the range of expected future commodity prices. Current natural gas and oil prices will make many possible developments difficult to justify on these grounds. Nevertheless, it is generally anticipated that prices will rise as world supply and demand once more become balanced. Even so, these frontier resources are also competing with other supplies such as from the oil sands. If development costs are similar, other issues such as GHG intensity of developments and local benefits will also influence choices.

3.3.2 Minerals (Mining)

As already discussed, the North has great potential for mineral development. Where developments have gone ahead, either the mineral was precious (for example, gold or diamonds), strategic (such as uranium) or bulk (like lead-zinc or nickel). In all cases, the ore concentration had to be very high to make the operation viable due to the extra costs imposed by remoteness.

Future scenarios will largely involve onshore mines. Many of these will seek tidewater as a transportation route for their products; hence, their relevance to Northern Oceans.

The precedents for shipping ores by icebreaking vessels have already been made and discussed in Section 2; these include Nanisivik on Baffin Island and Polaris on Little Cornwallis Island. In these cases, the concentrate was stored through the winter, then shipped seasonally (although the vessels still required significant ice capabilities). Further south at the Voisey's Bay mine development on the Labrador coast, year-round shipping is employed. The icebreaking bulk carrier *Umiak 1* was designed and built for this trade.

It can be expected that future developments will strive to extend the shipping season as long as economically possible. This leads to the challenge of more efficient icebreaking vessels, as well as the operation of year-round ports and new winter navigable routes to markets. These challenges are discussed further under the headings of "Shipping" and "Infrastructure".

Mining, milling and concentrating require considerable amounts of energy. At these remote sites any form of energy is expensive. Processes that can minimize energy requirements would greatly benefit northern mining developments. The availability of alternative energy sources that do not require long and expensive shipping is desirable. Wind power has been used to reduce imported energy requirements at one site. The high costs associated with providing northern mining energy requirements may in fact provide a better opportunity for alternative forms. The use of local LNG is another possibility and is mentioned again later in the context of a "green fuel" for the North.

3.4 Ships and Shipping

3.4.1 Early Beginnings

Marine craft have been used to successfully navigate the waters of northern Canada for millennia. Craft such as umiaks and kayaks have been built from locally available materials and used for hunting and transport. These boats, built using traditional knowledge, are elegant examples of indigenous design and engineering.

3.4.2 The North West Passage

Exploration for the fabled Northwest Passage as an alternative route from the Atlantic to the Pacific was carried out over several centuries after Pope Alexander VI, in the treaty of Tordesillas of 1494, divided the New World between Spain and Portugal and thus blocked access to China and the Spice Islands by northern European countries such as Great Britain and the Netherlands.

The actual existence of the Passage, however, was not confirmed until the 19^{th} century, when it was transited in multi-year trips by McClure (by ship and sled) and by Amundsen (by ship). It was not until 1944, that the Canadian-built RCMP schooner *St Roch* made the first continuous voyage through the NW Passage from Halifax to Vancouver in 86 days, under the command of Sargent Henry Larsen.

In the 1960s oil was discovered on the north slope of Alaska and a bold experiment was undertaken by Humble Oil (now ExxonMobil) to ascertain the feasibility of using icebreaking tankers to bring oil from Alaska to the east coast of the United States, using the Northwest Passage. The company converted the largest tanker in the US fleet, the *SS Manhattan,* into an icebreaking vessel and in 1969, with the Canadian Coast Guard icebreaker *John A MacDonald* in attendance (Figure 3.4), she made a successful transit through the Passage to Alaska and back again. This activity, although it demonstrated the potential for commercial ship voyages in northern waters, did not result in oil being exported from Alaska in this manner.

Figure 3.4: *SS Manhattan* and *CCGS John A. MacDonald* in NW Passage – 1969 (Photo: Capt. Joseph Osifat)

In fact, it is only in very recent times that any commercial cargoes have been transported through the Northwest Passage by sea-going cargo ships unaided by escorting icebreakers. The Canadian-owned icebreaking bulk carrier *MV Nunavik* (Figure 3.5) loaded a cargo of nickel ore at Canadian Royalties near the tip of the Ungava peninsula in Hudson Strait and sailed north on September 19, 2014. She reached the Beaufort Sea on September 28th and passed through the Bering Straits en route for China on October 1st.

Figure 3.5: 25,000 ton deadweight icebreaking Bulk Carrier, *MV Nunavik*, owned and operated by Fednav, Montreal, PQ – 2014 (Photo: Fednav)

It is likely that for the near- to mid-term future such voyages, which completely transit the Northwest Passage, will remain infrequent. Rather, shipping traffic will focus on supporting resource development, Arctic community resupply and maritime-based tourism in and out of the Arctic.

3.4.3 The 1970s – A Zenith of Canadian icebreaker Design & Construction

In the mid-1970s a Canadian company, Dome Petroleum, commenced serious activities to explore for oil in the Beaufort Sea. The first vessels built were evolved from conventional offshore supply vessel and anchor handling tug designs of the time, but with the application of icebreaking hull forms and ice-strengthened hull structures (Figure 3.6). These vessels were designed to operate during the open water season and into the new ice of early winter in support of exploration drilling for oil.

Figure 3.6: British Columbia-built icebreaking offshore supply vessels for Dome subsidiary Canadian Marine Drilling, Canmar
(Photos: BP-Dome Petroleum/Canmar)

By the late 1970s it became apparent that successful drilling in the Beaufort Sea would depend on the availability of significant ice management capabilities.

Dome-Canmar contracted for a new major icebreaking vessel (Figure 3.7) which incorporated a number of unique features:

- ice reamers extending beyond the moulded hull lines;
- a spoon-shaped bow with water lubrication system; and
- a single-screw mechanical drive propulsion system with ducted propeller.

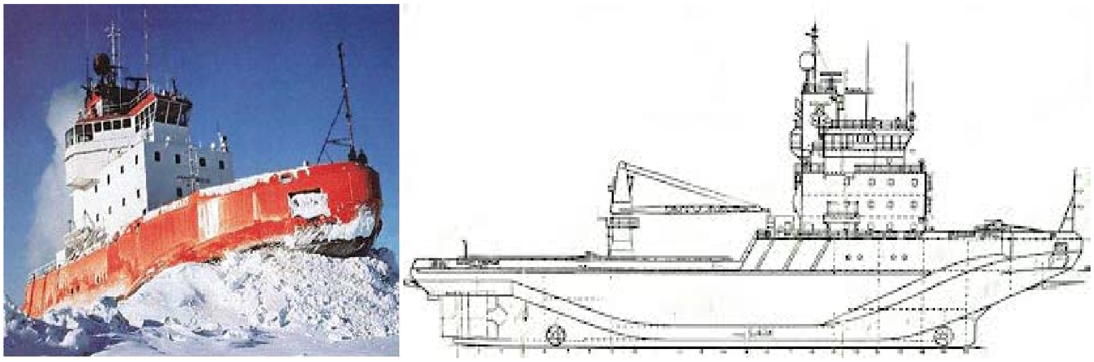

Figure 3.7: Saint John-built *Kigoriak* – Bow view during ice breaking and side profile view showing novel hull arrangement
(Images: STX Canada Marine [left]; Brian Small [right])

The resulting vessel, the *Kigoriak,* was built in Saint John and delivered to the Beaufort Sea by way of the Northwest Passage. Already recognized at the time of her construction, but even more in retrospect from today, the *Kigoriak* represents a turning point in icebreaker design.

Following the Dome Petroleum lead, Gulf Oil Canada, the other major offshore lease holder in the Canadian Beaufort Sea, decided to undertake an exploration program of its own. Gulf ordered two special-purpose drilling units, one floating, the conical drill barge *Kulluk,* and one bottom founded unit, *Molikpaq.*

To support these two Arctic mobile offshore drilling units, Gulf ordered 4 icebreaking support ships, two designed primarily for heavy ice management duties and two designed for more general offshore anchor handling and resupply duties.

These vessels performed well as part of the Gulf Canada Beaudril fleet. (Figure 3.8)

Figure 3.8: Beaudril icebreakers (Photo: Robert Allen Ltd.)

When there was a major drop in world oil prices in the mid-1980s, offshore exploration in the Beaufort Sea came to an abrupt halt. Many of the ships described above, however, found new duties under Russian owners supporting exploration activities in Russian waters. The *Kigoriak* remains in service today but renamed the *Talagy*, by her Russian owners, and three of the Beaudril icebreakers are now also in Russian service with the remaining vessel, the *Terry Fox,* currently in service as a Canadian Coast Guard icebreaker.

3.4.4 Current Northern Waters Shipping Activity

The Canadian Arctic is rich in mineral resources and over the past few decades, significant economic return has been gained by using ships to export a range of high-value minerals such as lead, zinc and nickel ore concentrates. This has been possible because, while mine and concentrate operations are year round, the shipping of ores can be done on a seasonal basis, avoiding the worst of ice conditions.

Mines in the High Arctic, such as Polrais on Little Cornwallis Island or Nanasivik on the north end of Baffin Island, have been depleted, successfully shut down and remediated, while the Nunavik and Voisey's Bay mines in sub-Arctic conditions are still in service. The location of these mines is shown on Figure 3.9

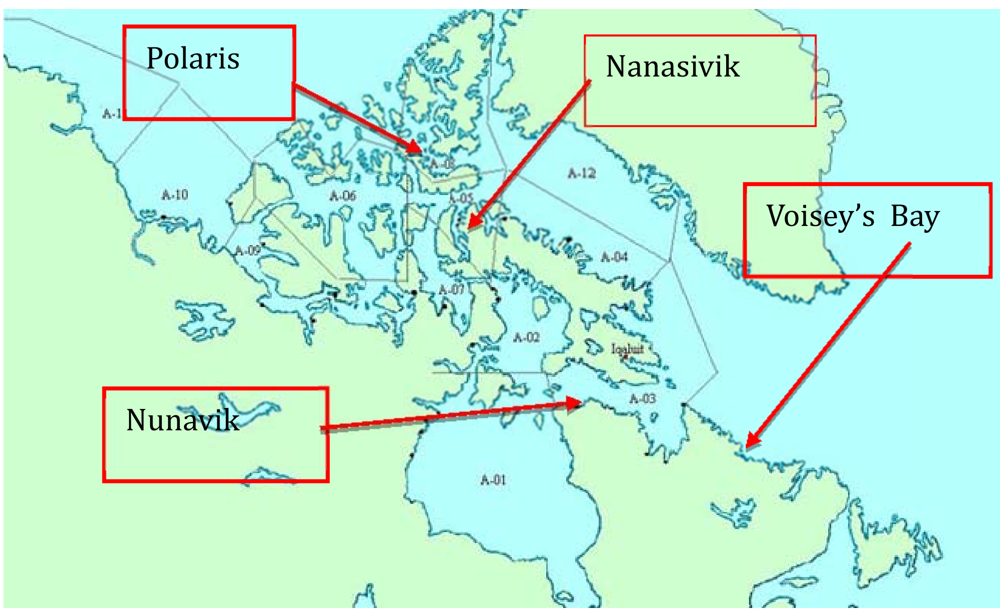

Figure 3.9: Location of Arctic and Sub-Arctic mines with marine export systems

All of these mines have been serviced by ships from the FedNav fleet. FedNav is a shipping company headquartered in Montreal and has world-class experience in Arctic shipping. The company operates three major icebreaking bulk carriers, the MV *Nunavik* referenced earlier (para. 3.4.2), and the MV *Arctic* and MV *Umiak* shown below in Figure 3.10-3.11.

Figure 3.10: Canadian-built *MV Arctic* (Photo: Fednav Ltd.)

Figure 3.11: *MV Umiak* bulker (Photo: Fednav Ltd.)

Recent changes in summer ice cover in the Arctic have led to much speculation about using trans-polar shipping routes to connect Pacific and Atlantic ports. Figure 3.12 shows alternative trans-polar routes being considered.

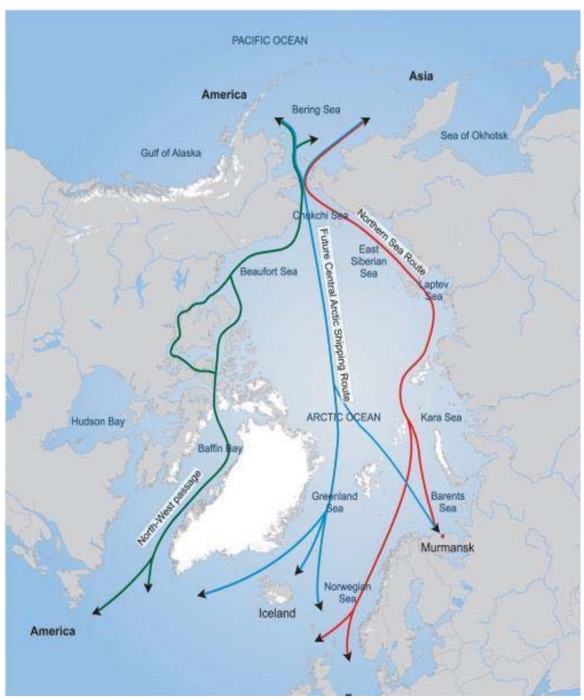

Figure 3.12: Alternative trans-Polar routes

However, the potential for significant trans-Arctic shipping is probably not high in general, and relatively low for the Northwest Passage. This is due to uncertainty of conditions and lack of accurate charting, readily available icebreaker assistance and infrastructure such as navaids.

While there has been some reduction in summer ice cover in certain areas of the Arctic, winter ice still makes navigation extremely difficult. Figures 3.13 and 3.14 illustrate the extent of ice cover in recent years: maximum ice coverage in March shows little variation over a 30-year period, and while summer ice minimum in September is somewhat below average, it is still sufficient to cause a hazard to navigation.

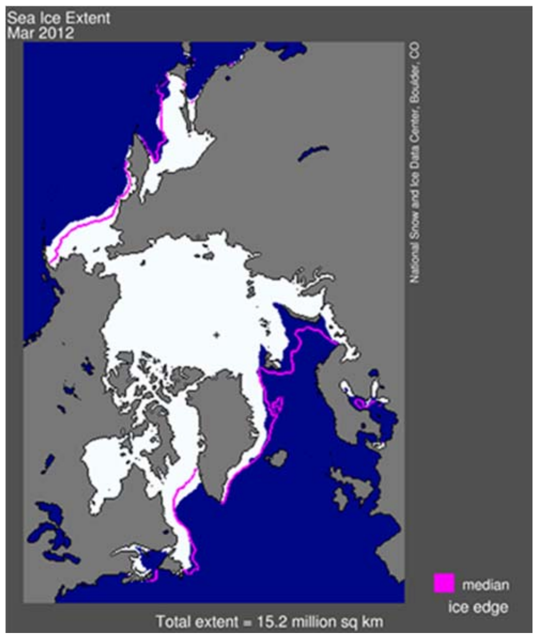

Figure 3.13: Maximum winter ice, Mar. 2013

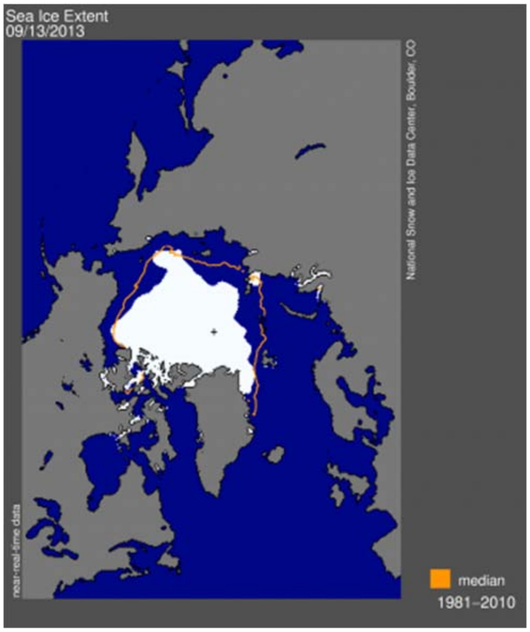

Figure 3.14: Minimum winter ice, Sept. 2013

3.4.5 Ships in Support of Sovereignty

Another important aspect of ships in the Canadian Arctic is sovereignty. The Canadian government currently has plans to build one heavy polar icebreaker (Figure 3.15) and a number of lower capability Arctic Offshore Patrol Ships (Figure 3.17) (AOPS). Unfortunately, as often happens, cost escalations and budget constraints are causing delays in these programs. Canada, at present, has only one heavy polar icebreaker, the *CCGS Louis S. St. Laurent*, (Figure 3.16) which entered service in 1969.

Figure 3.15: Planned CCG polar icebreaker (Image: Canadian Coast Guard)

Figure 3.16: *CCGS Louis S. St Laurent* (Photo: Canadian Coast Guard)

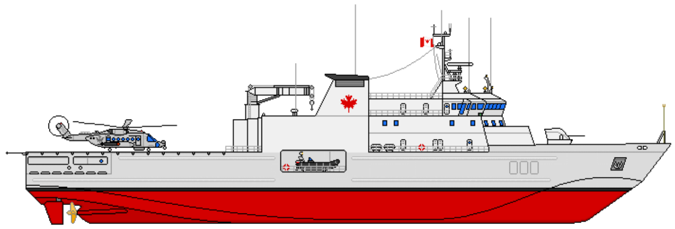

Figure 3.17: RCN Arctic offshore patrol ship
(Image: Irving Shipbuilding)

By comparison, the USA has a similar dearth of Arctic-capable surface ships, while Russia has a substantial and growing fleet of nuclear and non-nuclear icebreakers.

3.4.6 Arctic Marine Emergency Evacuation and Rescue

Canada can claim leadership in another important area of ships and shipping in northern waters, namely Emergency Evacuation and Rescue (EER).

Not only does Canada have experts in the development and execution EER plans, but there are also a number of research institutions and companies who are working on this topic.

Clearly when ships are operating at low temperatures in ice-covered waters the use of traditional lifeboats is inadequate. This is still an area of active R&D.

Figure 3.18 and Figure 3.19 below show some of the vehicles which have been developed by Canadians and are seeing service in other parts of the world.

Figure 3.18: ARKTOS amphibious lifeboat (Photo: ARKTOS)

Figure 3.19: Caspian icebreaking lifeboat designed in Canada (Photo: Robert Allan Ltd.)

3.4.7 Conclusion on Ships and Shipping in Canada's Northern Waters

Canada has strong capabilities in a number of areas, such as Arctic offshore oil and gas engineering and operations, and in all aspects of shipping in support of Arctic mineral extraction. Further, Canada has excellent research and development capabilities and world-class marine design expertise.

There are some weaknesses, however, such as the lack of action to urgently secure assets which will ensure Canadian Arctic sovereignty and the aging of Canadian Arctic engineering expertise which needs attention to ensure new expertise is being developed in the country.

3.5 Infrastructure

Under this topic we include ports and harbours as well as navigation systems and emergency response. Such infrastructure relates to many of the opportunities already identified.

Marine transportation is the primary mode for bulk resupply to Arctic communities, yet infrastructure in the form of ports and harbours is very much lacking. Several northern shipping companies (Desgagnes, NEAS, Northern Transport Company Limited (NTCL), Petro-Nav, Woodward) serve most communities through the annual sealift, which supplies basic goods, housing supplies and fuel for each year. Commercial re-supply comes from southern points of origin, one in the west and several in the east. In the western Arctic, most cargo is shipped by tugs and barges from Hay River down the Mackenzie River to Tuktoyaktuk for further distribution. Conventional low ice-class ocean-going general cargo vessels typically handle cargo in the eastern Arctic. Cargo is lightered ashore using small tugs and barges that are carried with the ships. There are only a few wharves in the Arctic, so cargo has to cross the beach. This is a slow and hazardous process that involves multiple handling of cargo. Floating hoses are generally used for fuel transfer – also a hazardous operation. Deepwater docks have been built as an integral part of mining operations for shipping out concentrate. The dock at Little Cornwallis was used for about 20 years and then removed. At Nanisivik the mining operation has also been wound up and the site cleared, but the dock has remained in place and refurbishment is planned so it can provide a support and refuelling base for DND and CCG vessels.

An assessment of current marine infrastructure indicates that it is very sparse in the North. In the Yukon none of the 17 communities have access to marine infrastructure. Four of the 34 communities in the Northwest Territories are served by marine traffic only, and 11 are served by both marine and road traffic. All 26 communities in Nunavut have tidewater access, but the only port, Nanisivik, is not associated with a community. Potential ports could be established at Rankin Inlet and Bathurst Inlet. Recently, a small craft harbour has been built at Pangurtung to support a local fishing operation. Not to be overlooked is the port of Churchill, which is used seasonally for grain shipment to international markets. It has been speculated recently that Churchill could be an export terminal for oils sands products (Canatec, 2013).

The deepwater oil and gas leases in the Beaufort Sea have been mentioned in Section3.2.1. In their exploration phase a shore base will be needed. If development occurs it is possible that a loading terminal for tankers may be used somewhere in the region, either offshore or on the coast. In both scenarios, the harbour at Tuktoyaktuk will likely play a role (as recently reviewed by Matthews (2014)).

Large mining and resource development projects factor in the cost of a deep-water dock as part of their infrastructure, both for shipping out product and bringing in supplies. A current example is the development of the Mary River iron deposit. Baffinland will be proceeding with an "Early Revenue Phase" which will require a smaller initial investment, shorter lead time, smaller annual production and only seasonal shipping. The project will build a dock and loading facility at the south end of Milne Inlet. Satisfactory docks have been built for Little Cornwallis, Nanisivik, Voisey's Bay and Deception Bay. Reduction in the cost of dock and harbour infrastructure would benefit any mining project in the North. One of the uncertainties is characterization of ice conditions, which leads to excessive conservatism in design. There is also room for innovations in the design of docks which will have limited service life and likely require removal at the end of the project.

The design and operation of harbours and terminals in ice-covered waters is different from in the south because of the ice. There are several issues, including: ice forces on harbour structures and moored vessels; protection structures for moored vessels; control of ice build-up due to repeated vessel transits; ice management techniques to mitigate these problems.

3.6 Northern Involvement and Education

A key part of creating value for Canadians from resource development in the country is to engage its citizens. Such engagement is not simply in jobs, but also in decision-making processes and in education to ensure meaningful and fulfilling involvement. We consider this to be especially important in areas where there may be few other opportunities, for example in the North.

Noting the region's demographics, we believe there is some urgency surrounding this issue which can also be classed as a significant opportunity.

The North has a high population growth rate and a high percentage of young people. For example in 2013, Nunavut had the nation's highest population growth rate at 2.5%. The median age in Nunavut is about 25, compared to 40 for the rest of Canada; the proportion of people under 15 years old is about 30%.

It is not the intent of this study to address potential social issues surrounding the above-motioned demographics, but only to suggest that northern involvement in Arctic engineering (and science) can provide very satisfying opportunities for its young people.

Such involvement can also be a channel for the integration of traditional knowledge that has been acquired over millennia by Northerners.

Outreach programs are conducted by engineering associations in other provinces to raise awareness of science and engineering in schoolchildren. If not currently in place in the North, these should be implemented. An early awareness and the creation of interest and excitement surrounding potential future engineering and scientific projects is a foundation on which to build an educated population who can then be meaningfully involved.

Beyond high schools, improved access to educational facilities in engineering and technology by Northerners is seen as a priority, and we advocate the commencement of instruction in engineering and technology at CHARS (see Section 2.4). This should be linked to expertise in other Canadian universities such as Memorial University of Newfoundland. The concept could be similar to the Ny-Ålesund research facility in Svalbard, which is managed by the Norwegian government.

4 Recommendations

The recommendations of this study are based on the following premises:

- There are significant resources in Canada's North, which if developed responsibly will create value for Canadians.
- In enabling Northern developments, employment and training opportunities for Canada's northern residents will be enhanced and Northerners will be empowered by participation.
- Furthermore, maintaining and enhancing our knowledge base also allows Canadians to compete elsewhere in the world in both providing consulting services and in creating joint ventures.
- Finally, the ability to maintain sovereignty and to understand and respond to climate change in the North will be enhanced by maintaining and exercising our Northern Oceans engineering capabilities.

Technical uncertainties and barriers to future resource developments have been discussed in this report. Several of these are already being addressed by industry and also through collaborative activities with institutes such as C-CORE, CARD and NRC, and universities such as Memorial. Federal funding is channeled mostly through NRC and universities. High priority engineering topics worthy of additional, collaborative and imaginative work include:

1. *Ice Mechanics and Loading:* The crux of Arctic offshore engineering is to understand ice mechanics and how ice creates loads on platforms and vessels. Local and global ice pressures are needed for design of both. There has been significant progress in this field to date by Canadian engineers who have used large-scale measurements to develop new theories and methods. The size effect is most important in global design and would benefit significantly from more full-scale testing and measurements with thick ice. Improved information on forces in pack ice is also seen as a research need, as well as the mechanics of interaction of sloping structures with thick ice.

2. *Floating platforms in ice:* In deeper Arctic waters, subsea production with pipelines back to shallower water is one possible scenario. Floating platforms will be needed for drilling and possibly for early production. There is a need to make these floaters as ice tolerant as possible in order to extend the drilling season and especially for relief well drilling. They would be disconnected if ice conditions become too severe. The ice can also be managed to reduce ice loads. The understanding of how the degree of ice management affects the ice loads and how to estimate them is still uncertain and there is a continued need to address this issue. Forecasting of ice and metocean conditions is an important component in these operations,

including such factors as pressured ice and sudden changes in the direction of ice movement.

3. *Arctic shipping:* Shipping is required for community access, tourism and transportation of resources. Ice loads on ship hulls in heavy ice, and efficient ice-worthy propulsion systems continue to be a worthy research topic. Navigational infrastructure will need attention.

4. *Terminals and harbours:* In ice-covered regions, terminals and harbours have different design and operational problems from those in the south. Dock facilities and berthed vessels have to be designed for ice interaction. If too much protection is provided by enclosures, the issue of ice build-up due to repeated ship transits can be a problem and ice management becomes critical.

5. *Safety and environmental protection:* The topic of escape and evacuation from vessels and platforms in ice is a unique issue to the North. Work has been underway on this topic, but improvements will be key to maintaining safety in harsher regions. Drilling of a same-season relief well poses difficulties as operations move further north, with shorter drilling seasons and more difficult ice conditions. The issue of oil spills is best addressed by prevention – which is dependent on sound design and impeccable operating methods. Even so, if oils spills do occur, it is paramount to understand their impacts and how to mitigate them. Ice can be advantageous in containing a spill, but recovery of the oil can be more difficult.

6. *Environmental characterization:* Safe and efficient design of engineering structures and vessels is also dependent on knowing the types of ice and other environmental parameters prevailing in an area. Climate change brings additional uncertainty in defining extreme ice features. Methodologies are needed to address this uncertainty. Of high importance is to understand and predict how multi-year ice will change in both occurrence and thickness.

Northern involvement and education deserve attention within the context of engineering for the Northern Oceans. It is recognized that traditional knowledge plays a role in engineering for Northern Oceans and that there is benefit from close relationships between engineers and northern residents through such as the Centre for the North, which provides a forum for research and dialogue on northern and Aboriginal issues.

The percentage of young people in the North is high and future developments can provide them with meaningful employment. Outreach programs are recommended to raise awareness of science and engineering among Northern schoolchildren. An early awareness and the creation of interest and excitement surrounding potential future engineering and scientific projects is a foundation on which to build an educated population who can then be meaningfully involved. Improved access to engineering and technology educational facilities by northerners is seen as a priority, and we advocate the commencement of instruction in engineering and technology at CHARS linked to expertise in other Universities in Canada, for example Memorial University. The concept could be similar to the Ny-Ålesund research facility in Svalbard which is managed by the Norwegian government.

One of the themes of this study has been to show that significant advances in knowledge flow from "doing" rather than "discussing". It is appreciated that resource developments themselves will occur without intervention, if the economics are favourable and regulations are fair. Nevertheless, there can be projects relating to infrastructure, collaborative research and communities which, if encouraged and funded, can lead to enhanced northern engineering capabilities. The team proposes for consideration several "visionary" projects and programs within the list below.

1. *Arctic LNG—Clean Green Fuel for the North*

   The Arctic has an abundant supply of natural gas both in the Beaufort Sea region and in the Arctic Archipelago. Arctic communities and activities need fuel. It is proposed to develop an Arctic LNG public–private partnership to supply LNG both for fuelling government Arctic operations and supplying local community needs. This would provide clean, green Arctic fuel that would, for example, allow year round icebreaker operations.

2. *Mobile Arctic Engineering Research Platform*

   In this concept an iceworthy ship would be developed to be the engineering experiment itself, rather than a platform for science laboratories.

   Ice transit experiments, hull and propeller loads, study of towing of arrays in ice, ice management strategy development, experiments to develop support of sub-sea developments in ice are possible functions, with Nanisivik as a possible northern base.

3. *Canadian Arctic Railway along the McKenzie Valley from Hay River to Inuvik*

   A Canadian Arctic Railway would provide a two-way system that could be used to deliver materiel for northern construction, as well as fuel and other essentials for local communities presently served by summer barge traffic on the McKenzie River. The system could bring Arctic oil to southern markets and would provide a strong logistics link to the western Arctic, further improving infrastructure and reinforce Canadian Arctic sovereignty. Further, the system, possibly fuelled by LNG, would allow for development of other natural resources such as minerals and forest products along its route.

4. *International Arctic Ocean-Space Engineering Experimental Station (IAOSEES)*

A permanent base is proposed on Hans Island, which is currently disputed territory in the Kennedy Channel between Canada and Denmark. The IAOSEES (pronounced *Eye-Oh-Seas*) would be jointly managed by Canada and Denmark as a shared facility available to members of the Arctic Council. This station would serve the need for large-scale experimentation to further advance Arctic marine & offshore engineering.

With regard to Arctic sovereignty, it is important to emphasize the need to have a strong presence. A sovereign state is represented by one centralized government that has supreme independent authority over a geographic area. There are responsibilities associated with this authority. For an Arctic state in the 21st century, these responsibilities and obligations can only be satisfied by the extensive use of technology, including ships, aircraft and remote monitoring systems. The Polar icebreaker *CCGS Diefenbaker* will be available when completed in some years' time. In the meantime, Canada has very limited capability; the Arctic Offshore Patrol Vessels now being designed and built have limited ice-transiting capability. While there is little evidence at present of a challenge to Canada's sovereignty in the North, Canada is ill-prepared to address any future challenge.

A parallel approach to sovereignty is to be active in the region. In this context, the initiatives suggested in this report would achieve much.

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Appendix A: Note from IPCC, 2013 (Summary for Policymakers)

A.1 Observed Changes in the Climate System

- Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia. The atmosphere and ocean have warmed, the amounts of snow and ice have diminished, sea level has risen, and the concentrations of greenhouse gases have increased.

    - Each of the last three decades has been successively warmer at the Earth's surface than any preceding decade since 1850.

    - Ocean warming dominates the increase in energy stored in the climate system, accounting for more than 90% of the energy accumulated between 1971 and 2010 (*high confidence*). It is *virtually certain* that the upper ocean (0−700 m) warmed from 1971 to 2010 (see Figure SPM.3), and it *likely* warmed between the 1870s and 1971.

    - Over the last two decades, the Greenland and Antarctic ice sheets have been losing mass, glaciers have continued to shrink almost worldwide, and Arctic sea ice and Northern Hemisphere spring snow cover have continued to decrease in extent (*high confidence*).

    - The rate of sea level rise since the mid-19th century has been larger than the mean rate during the previous two millennia (*high confidence*).

    - The atmospheric concentrations of carbon dioxide, methane and nitrous oxide have increased to levels unprecedented in at least the last 800,000 years. Carbon dioxide concentrations have increased by 40% since pre-industrial times, primarily from fossil fuel emissions and secondarily from net land-use-change emissions. The ocean has absorbed about 30% of the emitted anthropogenic carbon dioxide, causing ocean acidification.

A.2 Drivers of Climate Change

- Total radiative forcing is positive, and has led to an uptake of energy by the climate system. The largest contribution to total radiative forcing is caused by the increase in the atmospheric concentration of CO2 since 1750.

A.3 Understanding of Climate System and its Recent Changes

- Human influence on the climate system is clear. This is evident from the increasing greenhouse gas concentrations in the atmosphere, positive radiative forcing, observed warming, and understanding of the climate system.

    - Climate models have improved since the AR4. Models reproduce observed continental-scale surface temperature patterns and trends over many decades, including the more rapid warming since the mid-20th century and the cooling immediately following large volcanic eruptions (*very high confidence*).

    - Observational and model studies of temperature change, climate feedbacks and changes in the Earth's energy budget together provide confidence in the magnitude of global warming in response to past and future forcing.

    - Human influence has been detected in warming of the atmosphere and the ocean, in changes in the global water cycle, in reductions in snow and ice, in global mean sea level rise, and in changes in some climate extremes (see Figure SPM.6 and Table SPM.1). This evidence for human influence has grown since AR4. It is *extremely likely* that human influence has been the dominant cause of the observed warming since the mid-20th century.

A.4 Future Global and Regional Climate Change

- Continued emissions of greenhouse gases will cause further warming and changes in all components of the climate system. Limiting climate change will require substantial and sustained reductions of greenhouse gas emissions.

    - Global surface temperature change for the end of the 21st century is *likely* to exceed 1.5°C relative to 1850 to 1900 for all RCP scenarios except RCP2.6. It is *likely* to exceed 2°C for RCP6.0 and RCP8.5, and *more likely than not* to exceed 2°C for RCP4.5. Warming will continue beyond 2100 under all RCP scenarios except RCP2.6. Warming will continue to exhibit interannual-to-decadal variability and will not be regionally uniform.

    - Changes in the global water cycle in response to the warming over the 21st century will not be uniform. The contrast in precipitation between wet and dry regions and between wet and dry seasons will increase, although there may be regional exceptions.

- The global ocean will continue to warm during the 21st century. Heat will penetrate from the surface to the deep ocean and affect ocean circulation.

- It is *very likely* that the Arctic sea ice cover will continue to shrink and thin and that Northern Hemisphere spring snow cover will decrease during the 21st century as global mean surface temperature rises. Global glacier volume will further decrease.

- Global mean sea level will continue to rise during the 21st century (see Figure SPM.9). Under all RCP scenarios, the rate of sea level rise will *very likely* exceed that observed during 1971 to 2010, due to increased ocean warming and increased loss of mass from glaciers and ice sheets.

- Climate change will affect carbon cycle processes in a way that will exacerbate the increase of CO2 in the atmosphere (*high confidence*). Further uptake of carbon by the ocean will increase ocean acidification.

- Cumulative emissions of CO2 largely determine global mean surface warming by the late 21st century and beyond (see Figure SPM.10). Most aspects of climate change will persist for many centuries even if emissions of CO2 are stopped. This represents a substantial multi-century climate change commitment created by past, present and future emissions of CO2.

Appendix B: Case Histories

B.1 Introduction

In the following, a set of Case Studies are described, including Imperial-Dome-Gulf Exploration – Beaufort Sea, the Polaris Mine Project – Little Cornwallis Island, the Arctic Pilot Project – LNG from the Arctic Islands, Voisey's Bay Shipping – Labrador Sea, East Coast Project – White Rose, as well as some international case studies where Canadian expertise has been prominent: Kashagan field development – North Caspian Sea, and the Shtokman Field: Iceberg Loads for Floater in Barents Sea.

B.2 Imperial-Dome-Gulf Exploration – Beaufort Sea

At its zenith in the late 1970s to early 1980s, oil and gas exploration in the Canadian Beaufort Sea was a considerable enterprise. It involved thousands of Canadians (many local Northerners) as well as new technology developed mostly in Canada. It is an important case history because it created a significant body of Canadian Arctic engineering expertise and demonstrated how new methods for offshore operations in ice were developed and safely implemented.

The first northern oil development in Canada was the Norman Wells oil field in the Northwest Territories at 65^0 N (145km south of the Arctic Circle) on the MacKenzie River. The Dene knew of the existence of seeping oil and called the area *Le Gohlini* (meaning "where the oil is"). Alexander MacKenzie also reported the oil seeps on his journey down the river in 1789.The oil field was discovered by Imperial Oil in the 1920s and went into production with a small refinery to supply local communities.

Meanwhile the Geological Survey of Canada had assessed that the Canadian Arctic had considerable potential for oil and gas. Companies such as Imperial, having already the experience of working in the high north, obtained leases in the Mackenzie Delta which also extended into the Beaufort offshore. This was somewhat visionary because, at the time, the oil price was at about $3/barrel and no technology existed for offshore drilling and production in ice-covered seas. In 1961 the British American Oil Company Limited (BA), which later became Gulf Canada Limited (Gulf), completed the first exploratory drilling in the Mackenzie Delta. This was followed by onshore drilling for oil and gas at the Reindeer site on Richards Island by a consortium comprising BA, Shell and Imperial.

By the late 1960s, Imperial and others were drilling in the Mackenzie Delta where gas discoveries were being made. In 1968/9, on the US side, the Prudhoe Bay oil field was discovered, with an oil recoverable assessment of 10 billion barrels. This further spurred the Canadian oil companies to look offshore in the Beaufort, where seismic exploration conducted in the summer months (and from the ice) had indicated geological structures as large as that at Prudhoe Bay.

With this incentive, engineers in companies such as Imperial Oil started to look at methods for offshore drilling and production in the Beaufort Sea. The only comparable experience was with the Cook Inlet oil fields in in Alaska, which were under development. They had been explored for during the summer months, but platforms to resist the winter ice were being designed and installed. These designs were based on ice load methods for bridge piers because the Cook Inlet structures were mostly multi-legged and the ice was similar to ice in the sub-arctic regions of North America where bridges had been designed and built.

A similar approach was considered for the Canadian Beaufort Sea, but there were major differences. The open-water period was much shorter (July, August and September), and even then the polar pack was always to the North and could be driven inshore at any time in a matter of a few days, thus creating a major hazard for non-ice-tolerant open-water drilling. Also, the ice was considerably thicker (up to 2m level ice with much thicker ridges; still thicker multi-year ice that had survived more than one summer still could be present).

Clearly, new approaches were required. In 1969 a small group was established in the Imperial Oil Research Lab in Calgary to investigate ice effects on offshore platforms in the Beaufort Sea. They initiated research on the crushing strength of Arctic ice and field programmes to look at ice movement, ice thickness and morphology in the immediate area of interest. This industry group tapped into expertise in ice already established at the National Research Council in Ottawa and at Universities such as Laval and the University of Alberta. It should be noted that much of the academic research at the time was focused on river ice problems. Engagement with industry on issues of Arctic ice interaction with platforms gave opportunities for the universities and NRC to expand into this topic.

A landmark initiative was the establishment of the Arctic Petroleum Operators Association (APOA), based in Calgary. This was the initiative of the late Alex Hemstock of Imperial Oil, who had worked on the Norman Wells development and was a cold regions expert. He took the R&D already underway at Imperial and opened it up to other Canadian oil companies with Arctic leases. The crushing tests by Imperial became APOA Project No 1 in 1970. Most Arctic research and data gathering initiatives over the next few decades were joint-industry sponsored through APOA. When APOA was merged into the Canadian Petroleum Association (CPA) in about 1985, over 220 R&D projects had been conducted under its auspices. The reports from these studies are still available through the Arctic Institute of North America in Calgary and the NRC in Ottawa. It should also be noted that a similar sister organization was established to engage in Canadian East Coast research, the East Coast petroleum Operators Association (ECPOA). Later in the US, the Alaska offshore operators formed a similar organization, Alaska Oil and Gas Association (AOGA).

In addition to this R&D, Canadian consultants were engaged to develop platform concepts for the ice loads being developed. The initial outcome was that Imperial's first offshore well was successfully drilled from a dredged island in 3m of water in 1972. Then, over the next several years, followed a series of exploration drilling islands in water depths out to about 20m. Figure B.1 shows a typical island in winter conditions. Many of these islands were instrumented for ice pressures around them; ice interaction processes were monitored. These were the first wide structures in ice and an important learning was that ice failed non-simultaneously around them, at lower average ice pressures than on narrow structures such as individual piles. Theories for this process were developed which allowed lower ice design criteria for future structures.

Figure B.1: Dredged Island in the ice – used for exploratory drilling by Imperial Oil [Beaufort Sea, circa 1976] (Photo source unknown)

Natural sloped artificial islands proved robust, but their costs and time to construct increased with the water depth cubed. It was appreciated that by using a caisson-retained island, this trend could be mitigated. This was the next step in technology development, and the Tarsuit caisson-retained island and Esso caisson-retained island (with reusable caissons) were used effectively in the 20 – 25m water depth range. Figures B.2 and B.3 show these platforms. They were world firsts, designed and constructed by Canadian companies.

Figure B.2: Tarsuit caisson-retained island under construction, showing the concrete caissons – built in Vancouver (Photo: CANMAR)

Figure B.3: The Esso caisson-retained island [Beaufort Sea – 1985] (Photo: K R Croasdale & Associates Ltd.)

These structures still required dredged fill, and a land rig to be placed after construction. The next improvement was the mobile-caisson bottom-founded platform concept, with a drilling rig permanently mounted on the deck. These could be moved from location to location in the summer much faster by de-ballasting and refloating. The wells were drilled mostly in the winter. The first of these concepts was the *Molikpaq* by Gulf Oil Canada, followed by the single steel drilling caisson (SSDC) by Dome Petroleum (See Figures B.4 and B.5). Again, although constructed in the Far East, they were designed by Canadian engineers.

Figure B.4: Gulf Canada's *Molikpaq* drilling caisson [Beaufort Sea, circa 1986]
(Photo: G. Comfort)

Figure B.5: Dome Petroleum's SSDC platform
(Photo: Dome Petroleum/CANMAR)

Due to visionary leaders in the management of these early operations, the *Molikpaq* was instrumented for ice loads and considerable ice pressure data was collected. This formed the basis for future design criteria developed mostly through additional Canadian research both in industry and academia.

In terms of research, a concern, as the platforms were deployed in ever deeper water, was that of the loads due to thick multi-year ice for which little experience had been gained from the shallower-water platforms. To conduct research on loads due to MY ice, the research group at Dome Petroleum came up with the idea of going to where MY ice was more common. Searches of aerial photos collected by the Canadian Government suggested the intriguing location of Hans Island, a small rocky island in the Kennedy Channel between Baffin Island and Greenland at 81^0N latitude. Not only was MY ice common, it appeared that during the spring there was a flushing out of MY ice from the Arctic Ocean down the channel. During these movements of large ice floes, many collided with the island analogous to interaction with a large offshore platform (See Figure B.6). A team first went to study this process in 1980. They camped on the island with a small helicopter. They had minimal monitoring equipment: ice augers for thickness, survey equipment for dimensions and distances, film cameras and a stopwatch. As each floe impacted the island, it's time to stop was recorded, as was the width of interaction. Applying Newton's laws, it was possible to back calculate the ice crushing pressure exerted by the MY ice as it interacted with the rock. This was a simple but brilliant experiment and gave the design team in Calgary some numbers to use in the design of the Tarsuit Caissons, which were at that time undergoing regulatory review in Ottawa. The experiment was repeated three years in a row, with ever-increasing sophistication of monitoring devices. It became another landmark APOA study and attracted international participants.

Figure B.6: Hans Island (Photo: Michel Metge)

The *Molikpaq* and SSDC were the culmination of the platform technology developed for the Canadian Beaufort Sea. As the activity in the Beaufort dwindled due to low oil prices in 1986 and mediocre exploration success, these platforms were used in other regions. The SSDC drilled several wells in Alaska. The *Molikpaq* was purchased for use off Sakhalin Island as an early production platform. Canadian consultants were used in its reconfiguration for this application, as well as during the ice management activities that were required to support oil offloading in ice.

Ice management is the term used for the activity of breaking ice around a drillship or platform to reduce the ice loads. This was initially pioneered in the Canadian Beaufort to support a drillship operation conducted by Dome Petroleum commencing in about 1975. Dome had leases that were too deep for islands and bottom-founded caissons, so summer drilling with some extension into freeze-up was the practice. To support its operation, Dome built several icebreaking supply vessels. They were mostly designed in Canada under the leadership of naval architects hired by Dome, largely from Finland. A photo of the *Kigoriak*, designed and built in Canada in the record time of eight (8) months, is shown undergoing ice ramming trials in Figure B.7. These naval architects stayed on to continue in practice in Canada even after the Beaufort operations ceased and have consulted on behalf of Canada world-wide.

Figure B.7: The *Kigoriak* (Photo: STX Canada Marine)

A notable innovation to extend the capability of floating drilling in ice was the ice-capable round drill ship named the *Kulluk* (See Figure B.8.). This was designed and built by the Gulf Canada drilling subsidiary Beaudrill; as were the accompanying icebreaking supply vessels. One of these is now the *CCG Terry Fox*. The *Kulluk*'s innovative design was a first of its type; the vessel was capable of drilling in the Beaufort Sea well into December, while other drillships would have been shut down in October. Fortunately, the mooring lines were instrumented so that ice loads on the vessel were measured. This is another valuable data set for ice loads on vessels in managed ice and continues to be the basis for much analysis and for the validation and calibration of ice load models.

Figure B.8: The *Kulluk*: an ice-resistant round drillship developed by Gulf Canada [Beaufort Sea, circa 1985] (Photo: Brian Wright)

Another innovation pioneered by Canadian engineers and used in the Beaufort Sea was that of drilling from the ice itself. Drilling from a thickened floating ice sheet was first done by Panarctic Oils in the Canadian Archipelago in the 1970s (Masterson, 2013). Several gas discoveries were made but never developed. The same engineers who developed this capability recognized that ice could be thickened quickly by spraying water into cold air to increase the heat transfer and, therefore, freezing rates. This technique was applied to produce grounded ice pads in shallow water in the Beaufort Sea. After research to ensure their stability, these spray ice islands were used for exploratory drilling of 2 wells in the Canadian Beaufort and 5 wells in the Alaskan offshore. An example of one spray ice island constructed and drilled from by Esso/Imperial in 1988-89 is shown in Figure B.9.

In total, during the period 1972 – 1992 about 86 wells were drilled in the Canadian Beaufort.

The total discovered resources in the Canadian Beaufort are estimated at about 1.2 billion barrels of oil (mostly offshore) and about 10 TCF of gas (mostly onshore in the Delta). Although no production of either oil or gas has occurred yet from the Canadian Beaufort Sea, many of the activities during the exploration period were aimed at developing technology for production. In fact, all the ice load research and knowledge gained are applicable to production platforms. Much work was also done on pipelines both onshore and offshore, as well as on icebreaking oil and LNG tankers.

Until the recent oil price drop (2014-15), work was underway to study the development of existing discoveries, in particular the Amauligak field, which is estimated to contain about 300 million barrels of oil. This work is now on hold.

It is a fair final statement to say that the period of Canadian Beaufort oil and gas exploration between 1970 and 1992 created significant knowledge and Canadian expertise in Arctic offshore engineering that persists to the present day and is still in international demand (as other case histories will illustrate).

Appendix I shows a list of exploration wells drilled in the Canadian Beaufort Sea by date and platform type (from Callow, 2012).

Figure B.9: The *Nipterk* Spray Ice Island
(Photo: Esso Resources Canada/Imperial Oil)

B.3 The Arctic Islands: Exploration and Pilot Production

The following text is extracted from a paper by Dan Masterson (2013).

The story of oil and gas exploration in the Arctic Islands of Canada and in the Sverdrup Basin of that region is largely the story of Panarctic Oils Limited. Panarctic was incorporated May 27, 1966 by Federal Letters Patent and operations started in 1968 with the first seismic work. J.C. Sproule of Calgary was a major force behind its formation. Panarctic was an industry/government consortium established to explore for oil and gas in the Canadian Arctic Islands, with up to 37 participating companies. Panarctic drilled 150 wells over an area measuring some 850 by 1200 km. The most northerly well was located approximately 80°45′ N on Ellesmere

Island and the most southerly well was at 72°40′ N on Prince of Wales Island. 38 of these wells were drilled offshore from floating ice platforms in water depths of up to 550 m. 500 km3 (17.5 trillion ft3) of natural gas reserves was discovered over this period and small oil reserves were discovered at Bent Horn. All of the offshore wells attempted were drilled, logged and tested as planned, a proof of the viability of using ice as a support for drilling. In spite of large distances, extreme weather and permafrost, the operations were successful and had no lasting effect on the environment.

Exploring for oil and gas in the Canadian Arctic Islands presents enormous physical, logistical and organizational challenges. Exploration began in 1961 and continued until 1986. Panarctic Oils Ltd, an industry/government consortium, was formed in 1966 to pool resources for this challenging and expensive undertaking.

Panarctic's effort formed the principal one, and they drilled 150 wells, 38 of them being offshore from floating ice platforms thickened to between 5 and 6 m. Conventional land rigs were used to drill both the onshore and offshore wells. Rig design was modularized to improve efficiency.

Panarctic collected 35,000 km of seismic line data during the time it operated, 16,000 km of this being from the offshore ice pack. Ice thickness was measured at

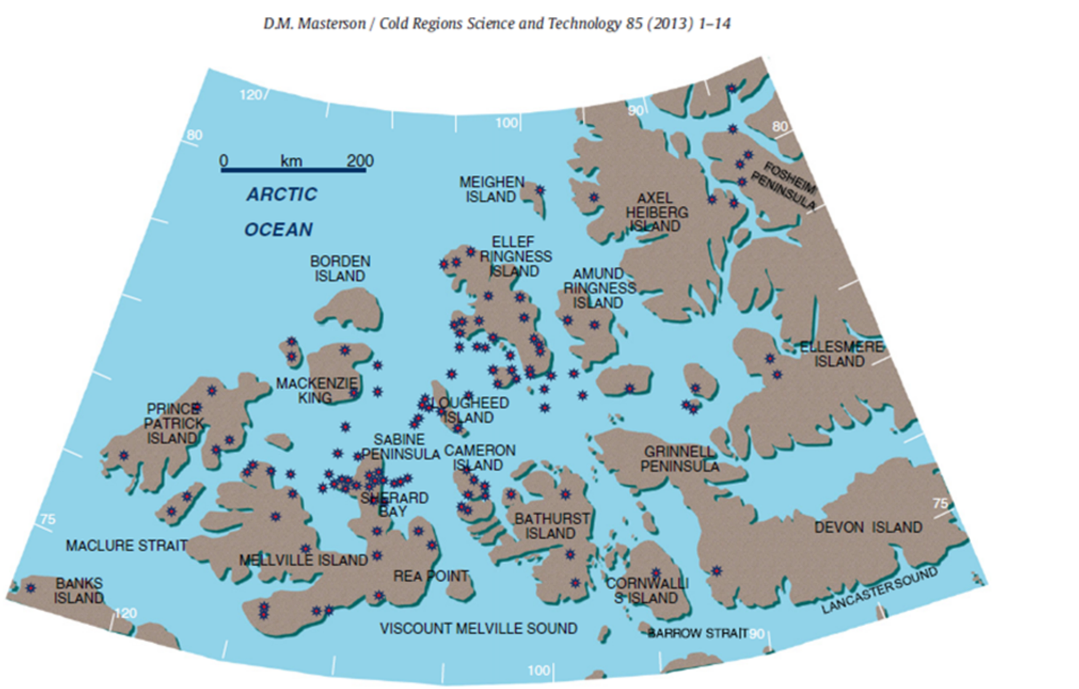


Figure B.10: Map of Arctic Islands showing the wells drilled (Masterson, 2013)

Transportation over large distances under hostile weather conditions was effected using aircraft and overland and over ice vehicles, both standard trucks and all-terrain vehicles. Supply of rigs, equipment and bulk material from the south occurred using sealift and Hercules C-130 transport. Crew changes were accomplished by Lockheed Electra and 727/737 aircraft. These aircraft landed on land strips or offshore on strips prepared on the sea ice. Hercules aircraft brought rigs and supplies to the remote locations. 253 loads were required. Helicopters, such as the Sigorsky S61, ferried construction equipment and camps to sites at start-up.

Well costs were relatively low for a frontier area. An onshore well could be drilled to a depth of 3000 m for $11 to $12 million. An offshore well of similar depth would cost $22 to $23 million. Early wells were drilled for $2 to $4 million. Later wells cost more because of several factors, including increased depth of the wells necessitating larger and more sophisticated rigs and because the operation included more stringent health and safety measures and more sophisticated and costly camps and related support.

Drilling offshore from ice platforms required continuous quality assurance during construction and performance monitoring during drilling. Basic information was relayed south and to NRC in Ottawa as part of the daily construction and drilling reporting.

A trial gas production was completed at Drake F-76 in 1978. An offshore well was drilled from a floating ice platform and a pipeline was connected from shore to the well using the sea ice as a support. Two 152mm flowlines, both heat traced, one insulated and one not insulated in a bundle were installed. Maximum flow of 10 m3/s at 10 MPa pressure was achieved during the flow test. The well was shut in in November 1978 and was plugged and abandoned in 1995.

Panarctic discovered a small oil field at Bent Horn on Cameron Island in 1974, and between 1985 and 1997 2.8 million barrels of oil were tankered south during the late summer/early fall period.

B.4 Polaris Mine Project – Little Cornwallis Island

The Polaris Mine was the world's most northerly metal mine, located on Little Cornwallis Island, about 100 kilometres north of Resolute. Underground mine construction started in 1980, with first production in 1981. Annual ore in production continued until the mine was closed in 2002, with an annual output of 250,000 to 300,000 tons of zinc and lead concentrates. These concentrates were stored in the large building shown in Figure B.11 and during the summer shipping season were transported to Europe.

Figure B.11: Polaris Mine site, showing accommodation, mill, storage shed and marine dock (Photo: Tek Resources)

The Polaris Mine project has a number of features relevant to Northern Oceans. Not only did it successfully export its ore concentrate by ship to international markets for over 20 years, but the development was also a prototype for building large-scale integrated barge-mounted facilities in southern Canada and bringing them north. This saved considerable time and effort over "stick-building" a plant on site.

Figure B.12: Process barge being towed north (Photo: Davie Shipping)

The entire mineral processing plant, power plant and workshop were built upon a barge, which was towed 5,600 kilometres from Quebec to the mine site. The barge was then floated into place in a pre-excavated berth, which was drained and back filled.

One important aspect of the project from a marine engineering point of view was the successful use of a sheet-piled cellular dock structure in a quite active channel where the dock was exposed to significant heavy winter ice.

Figure B.13: Export of ore concentrates with ship alongside dock
(Photo: Tek Cominco)

Figure B.14: *MV Arctic* icebreaking bulker, the main transport ship for Polaris Project (Photo: Fednav Ltd.)

The project is also important for northern engineering in that it has gone full cycle from exploration to development to operation to decommissioning to reclamation.

Figure B.15: Polaris project after decommissioning and reclamation (Photo: Tek Cominco)

B.5 Arctic Pilot Project – LNG from the Arctic Islands

Large reserves of natural gas were identified in the Canadian Arctic Islands between late 1960s and early 1980s, and a major project, the Arctic Pilot Project (APP), was conceived to answer important questions relating to developing a feasible solution to transport gas from the Arctic to eastern Canadian markets. The APP, led by PetroCanada, was one of the leading Arctic projects in early 1980s and significant development work was undertaken on advancing Arctic marine technology before the lower energy prices of the mid-1980s put the project on the shelf.

The pilot project was designed to address two questions:

- Could liquefaction facilities to handle 250mm standard cubic feet/day be built on an environmentally and economically sound basis, given that the location on Melville Island could be expected to result in conventional facilities that would cost at least five times that of facilities built in settled areas?

- Could large icebreaking LNG carriers be designed and built to operate safely year round in Arctic waters from Bridport Inlet to southern Canadian terminals?

The principal areas where advances in Arctic marine technology were made related to the design and engineering of the northern marine terminal for year round use, the barge-mounted LNG plant and the icebreaking LNG carriers.

In addition, significant developments were made in the areas of environment definition relating the basis of design for Arctic marine navigation and in numerical simulations for ice-transiting ships.

Melville Island Facilities

These facilities included the gas transmission line across Melville Island, to a barge mounted LNG plant and storage, and the Bridport shipping terminal, as shown on Figure B.16.

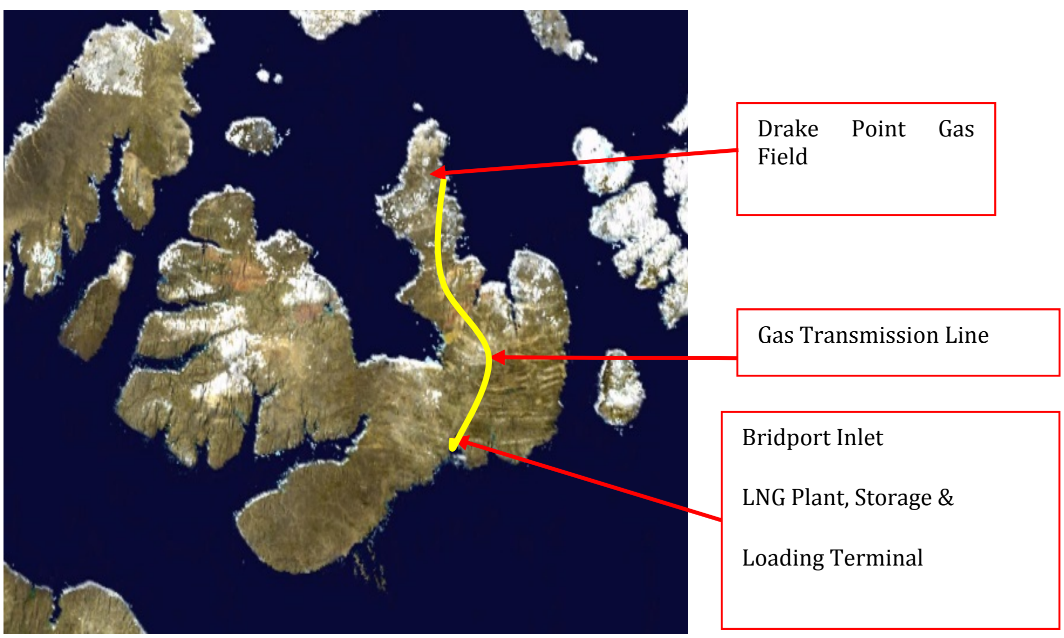


Figure B.16: Proposed Melville Island facilities

Bridport Marine Terminal

The export shipping terminal was to be located on the north shore of Bridport Inlet, a well-protected natural harbor on the south coast of Melville Island. The site was well situated for approach by sea, permitting a straight-in run from Viscount Melville Sound.

After examination of sites in the area, it was decided that the most suitable location for the terminal would be just east of the Mecham River Delta. This area is of a typical Arctic delta soil structure with frozen fine grain sands, silts and clays. Design of the Bridport shipping terminal was based on detailed technical and bathymetric information acquired during the spring of 1978 and on experience with an operating facility at the Nanisivik mine site on Baffin Island.

The design was based on a rock-filled gravity structure in which the rock is contained by interlocking steel piles driven from an ice platform. The circular sheet metal cells were to be about 25m in diameter, while the main pier was to be about 450m long and comprising 6 single and 1 pair of cells with a full length access roadway on a backfill foundation.

Berthing of vessels in ice-filled waters is well known to be very difficult. Many situations are recorded when vessels could not position themselves satisfactorily to proceed with and complete their loading or unloading procedures, due to the presence of ice at the berth interface. These difficulties, which were compounded by extremes of temperature, were confirmed by an ice basin study. It was concluded that an active and reliable system of ice management or control of the ice cover within the terminal area was required, otherwise successful docking could not be assured year round.

The barge-mounted liquefaction plant and storage facilities were planned to be constructed in shipyards in southern Canada and towed to Bridport Inlet during the six-week open-water season. This method was chosen in order to control costs and schedule and to reduce the impact of construction on the northern environment and economy. These floating facilities were to be moored inside a protected dock structure that was also to act as the LNG carriers' loading terminal.

Marine Transportation

Harsh environmental conditions (2m level ice, rubble ice fields, up to 5 ice ridges per mile, high winds, low temperatures, extended periods of darkness and the presence of icebergs in Baffin Bay and the Labrador Coast) made planning year-round marine transportation along the proposed route quite challenging. The main shipping route alternatives are shown on Figure B.17.

To assess the capability of the proposed marine fleet to operate year round, lifting the required production and safely and efficiently transporting the LNG to market, PetroCanada developed a sophisticated computer simulation tool with which the size and performance of any component (including the plant, storage and ships could be varied), thus allowing an assessment of the resulting system performance, including any change in the delivered cost of the LNG to southern markets.

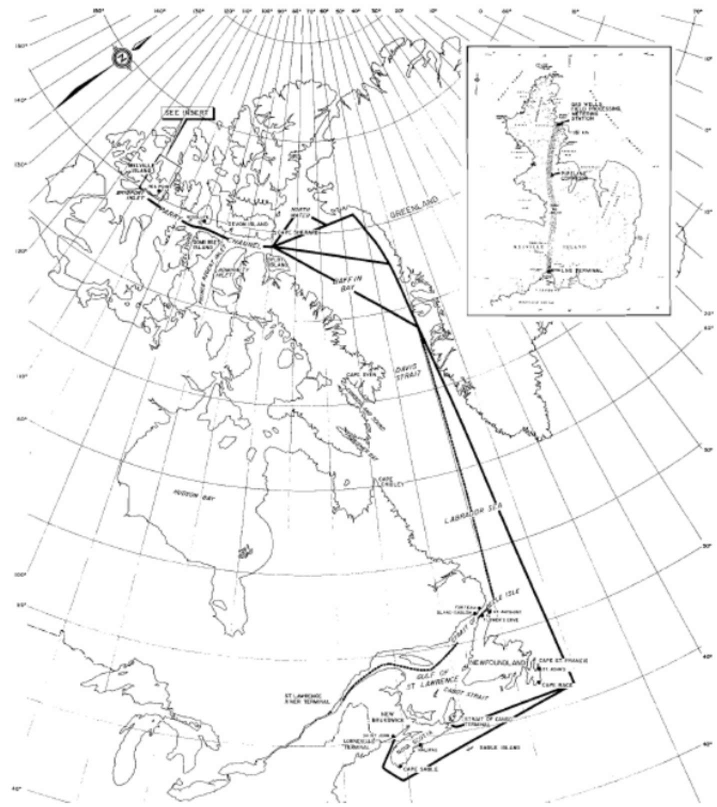


Figure B.17: LNG Shipping Routes – Melville Island to Eastern Canada

The marine transportation simulation program has four basic component models:

- The *Environmental Model* consisted of a bank of information on the environmental conditions along the route with respect to time. These conditions covered 6 full years, 1972 - 1978, for which good data were available. The data included ice thickness, ice coverage, ice type, ice pressure, iceberg density, ambient air temperature, visibility, and wind velocity and direction. This information was obtained from satellite imagery, local observations, field studies and over-flights. Three over-flights were conducted in the spring of 1978 to further study ice conditions. These flights are complementary to satellite imagery; they identified the number of ice ridges by means of impulse radar (IR), side-looking airborne radar (SLAR) and thermal IR. In addition, an on-ice ridge study was conducted in Viscount Melville Sound (See Figure B.18). This study involved the cross-sectioning of the 40 ridges of varying sizes and types in order to determine energy required to transit, degree of consolidation and internal strength. This study provided ground-truthing of over-flights.

Figure B.18: On-ice survey of marine route in Viscount Melville Sound
(Photo: Hydrometrics LLC)

- The *Ship Performance Model* contained a number of mathematical representations of the ship's performance in given ice conditions, including level ice, ridges, multi-year ice and broken ice. These equations of ship motion were derived from a series of tank model tests.
- The *Facility Manipulation Model* monitored the progress of the vessels. It also recorded and integrated the energy and time expended for each leg of the route.
- The *Presentation Output Logic Model* converted the generated outputs, presenting such information as elapsed voyage times, fuel consumed, boil-off generated and LNG delivered.

From studies carried out with this tool, the two vessels proposed would have had an LNG cargo capacity of 140,000m^3 each and were 335m long by 40m wide. Figure B.19 shows an artist's impression of these ships.

These Arctic Class 7 vessels were designed with 180,OOO bhp, four to five times that of standard LNG ships of the day, of comparable size, and they would have had more than double the hull steel weight. Based on all work and studies carried out, it was concluded that carriers could be built which could operate year round from Bridport Inlet to the Canadian East Coast.

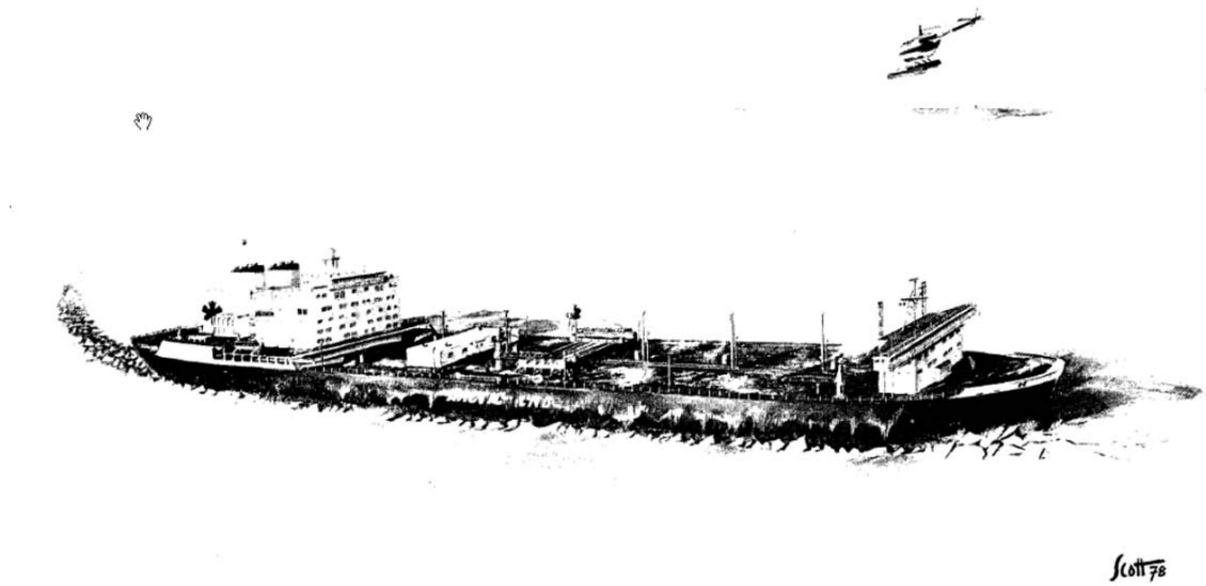


Figure B.19: Artist's impression of icebreaking LNG carrier

Regasification Terminal

The APP planned potential regasification terminals at one of three potential locations in Eastern Canada: on the St. Lawrence River, downstream from Quebec City; on the Strait of Canso, Nova Scotia; or at Lornevelle, New Brunswick. This facility would have provided a terminal dock and unloading facilities for the LNG carriers, plus two 100,000m^3 storage tanks to provide the necessary storage.

Environmental

The APP was to be designed, constructed, and operated with minimal disruption to the Arctic environment. The ecosystems on Melville Island are of low productivity and the island has limited precipitation, intense cold, and very short growing seasons. In contrast, some marine ecosystems from Eastern Parry Channel to the Scotian Shelf are highly productive. However, the LNG carrier route has been chosen to minimize encounters with such systems.

LNG Safety

Ocean shipping of LNG has been carried out since 1959. Shipments have been made in climates from tropical to sub-Arctic. These operations have had an excellent safety record, which can be attributed to the high quality of LNG carrier design, the selection and training of LNG carrier crews, and the effectiveness of their safety procedures. The two APP carriers and terminal facilities would have met or exceed the design, operation, and safety criteria of all such carriers and facilities currently in service around the world.

The safety of the Arctic Pilot Project was to be enhanced by:

- the strength of the structural design, the high level of propulsive power and the superior maneuverability of the icebreaking carriers;

- the safety distance from coast lines and population centres that was to be maintained by the carriers; and

- choice of location for the terminal facilities, both in the North and South, well removed from densely populated areas.

Conclusions

Although the Arctic Pilot Project never became reality, it did provide an opportunity for significant advances in Arctic marine technology, specifically in the following areas:

- northern marine terminals designed for year round use,

- barge-mounted plant for northern resource projects, including oil and gas and mining,

- simulation of Arctic marine transportation systems, which allowed a variety of options to be examined for technical and commercial feasibility, and

- design of large icebreaking ships capable of carrying bulk liquid and dry cargoes.

One lesson that may be worth further consideration is that by initiating a visionary project, many advances can be made that may have enduring value. US President Kennedy initiated such as visionary project with his injunction to land a man on the moon within a decade; while the APP may not quite be in that league, it did create similar value on a somewhat smaller scale.

It may point us to the value of a future Arctic visionary project which could provide an excellent means to focus Northern Ocean engineering developments, rather than continuing the current practice of having individual research and development efforts ongoing, perhaps within a road map but more often largely independently of one another.

B.6 Voisey's Bay Case Study

Background

The Voisey's Bay nickel deposit was discovered in September 1993 by two diamond prospectors. The find was one of the most significant mineral discoveries in Canada in the late 20th century. It is estimated to contain 141 million tonnes at 1.6% nickel. After several years of negotiations, the find was sold in 1996 to a Canadian mining company, Inco, for $4.3 billion. This was followed by 6 years of negotiations with the government of Newfoundland and Labrador, as well as with the Labrador Innu and Inuit, before an agreement to exploit the resource was reached in 2002. The mine began operation in 2005, with the first concentrate shipped in October of that year. In 2006 Inco was purchased by Vale and is now known as Vale Canada.

The Voisey's Bay mine is located in northern Labrador, about 35 kilometres southwest of Nain. The project encompasses a mine and concentrator at Voisey's Bay and port facilities in Edward's Cove, Anaktalak Bay. The mill is adjacent to the mine and uses crushing, grinding and flotation to produce concentrate. The concentrate is trucked 11 km to a storage building at Edward's Cove. The mine currently is an open pit operation, but is expected to move to an underground operation in about 2023 and continue until 2040. The current workforce is about 450 and operates on a fly-in-fly-out basis; with the underground operation, about 350 additional workers are foreseen.

From a Northern Oceans perspective, the project is of interest because the presence of sea ice from December through to June. This affected the design of the wharf, shipping out of concentrate and traditional use of the ice cover by local residents. These engineering and local factors had to be addressed and reconciled.

Ice Conditions

The port facilities in Edward Cove are at the end of an approximately 90km-long passageway between numerous islands leading in from the Labrador Sea. The position of the landfast ice edge varies throughout the winter, typically reaching a maximum in March, and the outer extent is variable from year to year. The ice in this passage is landfast and can reach thicknesses greater than 1m. Ice conditions beyond the belt of islands are characterized by the southerly drifting Labrador pack, which is present January through to late June. It width can vary from 50 to 200 km. Drift rates of the pack are from 20 to 120 km/day. Old ice at concentrations of one tenth can be found in the pack from February to mid-June. The pack comprises greatly deformed ice in floes some 5-8m thick and 50-90m across; however, the average thickness of the pack is about 1.5 to 2 m. The boundary between the landfast ice and the moving pack is a shear zone with ridges up to 5m high and extending for tens of kmkilometres. This zone, which may also be under pressure, presents a formidable obstacle to navigation. Finally, icebergs of various sizes are present year round along the Labrador coast.

Marine terminal

The marine terminal at Edwards Cove facilitates concentrate export from the mine's operations and offloading of re-supply cargo (See Figure B.20). The terminal is used for year-round shipping and the bay is subject to ice conditions. Therefore, in addition to normal requirements on the terminal, ice loading had to be considered in the design and construction (MacPherson and Kullmann, 2008). As is the case for many Arctic locations, the terminal is located in an environmentally sensitive area. This limited the scope of the in-water work. Documented experience at other wharves in the Canadian Arctic and local measurements were used to establish the average and extreme ice conditions for design. Canadian standards CAN/CSA S471-92(1992) and CAN/CSA S6-00(2000) were used to establish ice loads and design ice pressures. A characteristic of the landfast ice and tidal range of about 2m is the build-up of a large ice bustle that could limit access to the wharf face. A cantilevered wharf deck was incorporated to allow the ship direct access to the wharf face. A steel sheet pile cell (SSPC) structure was used for the wharf. The SSPC structure selected to form the wharf structure was an economical solution to satisfy the poor ground conditions at the site. However, the sheet pile interlocks comprising the structure are highly susceptible to ice-loading damage. Therefore, a means of strengthening the cell sheet piles was needed to withstand the high localized ice pressures. The strengthening system developed was to install of a number of precast reinforced concrete panels designed to withstand ice impact forces. These precast panels were installed directly behind the sheet piles to provide increased resistance.

Figure B.20: Marine terminal showing wharf, shiploader conveyer, concentrate storage building and *MV Umiak I* approaching wharf (http://www.vale.com/canada/EN/business/mining/nickel/vale-canada/voiseys-bay/Pages/default.aspx)

Ship and shipping operation

A key element of the success of the Voisey's Bay project is the provision of year-round shipping of concentrate from the site. With a long-term contract covering transportation of concentrate, FEDNAV, a Montreal-based Canadian shipping company with extensive experience in the Arctic, ordered the *Umiak I*, a 32,000 tonne icebreaking bulk carrier (See Figure B.21). The vessel is DNV class ICE-15, one of the highest ICE classes, and is capable of breaking 1.5m thick ice unassisted. The *Umiak I* is the most powerful vessel of its type. It incorporates an icebreaking bow, a water wash system to help reduce friction in ice, a V-shaped stern and an ice knife to protect the rudder - all features that FEDNAV's operational experience in the Arctic showed to be necessary for safe and efficient operation in ice. When ice conditions exceed those for continuous forward progress through the ice, for example ridges or thick pack ice floes, the vessel has to reverse and ram the ice. The 22-MW engine drives a single controlled-pitch propeller in a nozzle, which allows for quick reversal of thrust, high thrust at low speeds and protection of the propeller from ice damage. Each nickel concentrate cargo is worth several hundred million dollars, so reliable and timely operation ice critical.

Figure B.21: *Umiak I* in ice (Photo: Department of Fisheries and Oceans Canada)

In addition to the technology of the vessel itself, *Umiak I* uses the Enfotec IceNav system, a shipboard navigational software package to display satellite imagery with an overlay of radar from a marine radar. The main constituents of the system are the navigation module and the marine radar module, operating on a single PC with displays on two monitors. The two modules are completely integrated with route plans and ice information overlaid on one monitor and current marine radar on the other monitor (See Figure B.22). The ice information, including forecasts of ice pressure from the National Research Council, is provided by the Canadian Ice Service. IceNav facilitates safe and efficient route planning and navigation in ice.

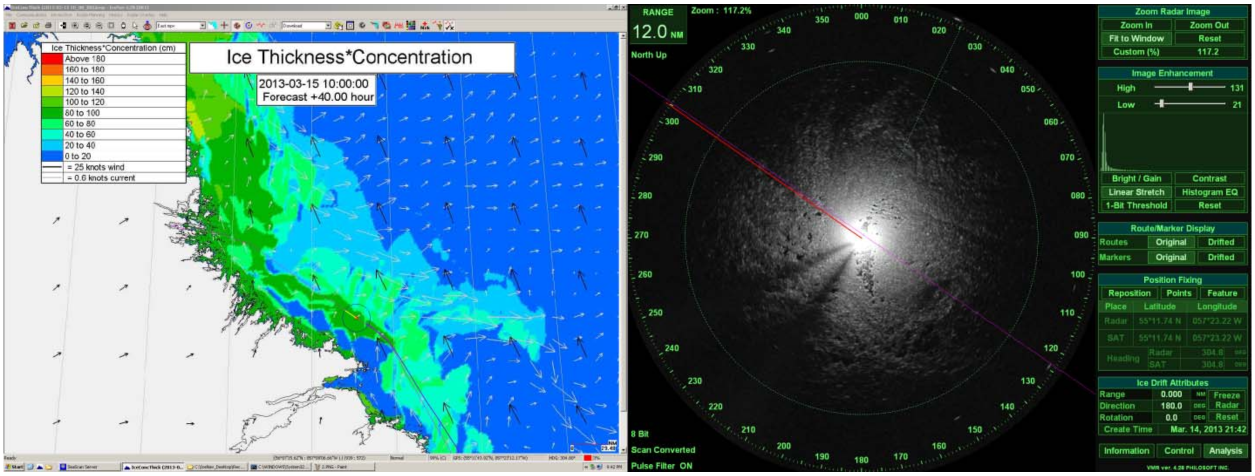


Figure B.22: EnfoTec IceNav displays of ice conditions and marine radar on the Labrador coast (Screen capture courtesy of Ivana Kubat, NRC on board *Umiak I*)

Shared use of the landfast ice cover

This topic moves away from engineering, but demonstrates that projects in the Arctic have to consider aspects other than those directly related to technical issues. The ice cover in the winter is a convenient surface for travel by local residents (Rowell and Metcalfe, 2005a). It was necessary to develop a shipping schedule that would respect the traditional use of the landfast ice cover and still allow a viable shipping operation (Rowell and Metcalfe, 2005b). The winter season has been divided into sections. In the early part of the winter, December 7 to January 21, no shipping is allowed. Then, from January 22 to April 6, provision is made for four nickel concentrate shipments. During this period the ship always operates in the same track, margins of the broken track are marked, a pontoon bridge placed across the track at a convenient crossing place is temporarily moved for each transit, and public notices of timing of ship transit in and out are made. Again, from April 7 to May 21, no shipping is allowed. Finally, from May 22 to December 6, shipping of nickel and copper, plus any other shipments is allowed. This system has been successfully used for a number of winters.

B.7 East Coast Development: White Rose

Three oil fields are already in production on the east coast of Canada: Hibernia, Terra Nova and White Rose. The Hebron offshore platform (gravity-based) is under construction, and a wellhead platform tied back to the existing *SeaRose* FPSO is being considered for the White Rose project. All of these developments have taken place in areas where sea ice and icebergs pose a challenge to the design of installations. Two strategies with regard to possible interaction with icebergs have been considered. The structure can be designed to resist iceberg loading: for example, gravity-based structures, which generally cannot be moved from location. Significant effort is made to detect icebergs using radar and other means, and to remove threatening icebergs by towing. Floating structures, on the other hand, can be designed to disconnect.

Pack ice can be expected at the White Rose location every few years, with 5/10 coverage 1 out of 4 years. Ice is present for an average 17 days a year, with an average thickness of 0.4 metres. The average annual number of icebergs in the degree square was taken as 0.95. The derived length distribution is shown in Figure B.23, with the management policy illustrated in Figure B.24.

The *Terra Nova* and the *SeaRose* are examples of turret-moored disconnectable Floating Production, Storage and Offloading units (FPSOs). The strategy in this case is to plan disconnection and removal of the unit if an iceberg cannot be removed. There is also the situation that detection of icebergs can be less reliable in the presence of high sea states, and at the same time smaller icebergs will be accelerated by the wave action, with much increased velocity and consequently kinetic energy.

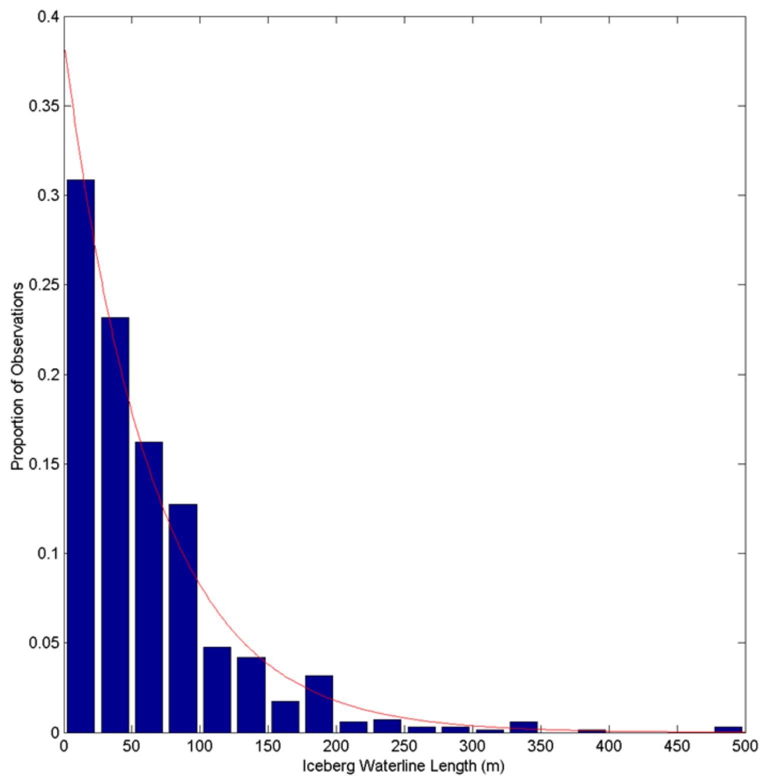


Figure B.23: Iceberg length distribution (Jordaan *et al.*, 2014)

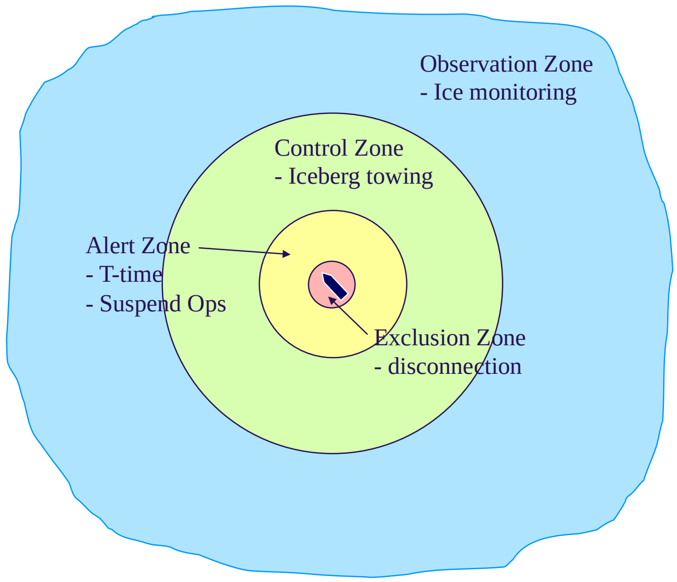


Figure B.24: Strategic ice management (Jordaan *et al.*, 2014)

The situation described poses a complex situation for design; the solution was found by means of probabilistic analysis. Methods based on this approach have been pioneered in Canada, together with guidance on safety levels in CSA S471 (Canadian Standards Association Standard: General Requirements, Design Criteria, the Environment, and Loads) and ISO 19906:2010 (Petroleum and Natural Gas Industries—Arctic Offshore Structures). The analysis accounted for factors such as areal density of icebergs, ice management, environmental conditions including sea state, and the mechanics of the interaction. Design was based on Safety Class 1, wherein failure would result in great risk to life or a high potential for environmental damage, for the loading condition under consideration with a Target Safety Level of 1 in 100,000 years or 10^{-5} per annum.

The final recommendations were made regarding local and global pressures from potential collisions with ice. These formed the basis of the design and selection of steel structure and plating. Design checks on structural response were also carried out by the team in St John's. Probabilistic methodology, together with developments in the understanding of ice mechanics, has led to much improved competitiveness of the designs, accounting for cost and safety.

Figure B.25: The White rose development showing the *SeaRose* vessel and tanker (http://www.offshoreenergytoday.com/canada-approves-amendment-to-huskys-white-rose-fdp/)

Figure B.26: The *SeaRose* under construction [Marystown, NL – circa 2005] (Photo: Kiewit)

B.8 Kashagan Field Development – North Caspian Sea

The North Caspian Sea is ice-covered for 3–4 months each winter. The ice is much less severe than in the Arctic Ocean; nevertheless, ice has significant effects on the design and operation of offshore platforms and pipelines. In 2000 the Kashagan field was discovered and is estimated to contain about 13 billion barrels of recoverable oil, making it the world's largest discovery in the past 30 years. Partners in this development include ExxonMobil, Shell, Total, ConocoPhillips, ENI and KazMunayGas. The Kasahagan field is about 70km offshore but the water is shallow, at only 4–7m.

In late 2000 a Canadian group (KRCA) was invited by the Kashkagan consortium to bid on collecting ice data and developing ice design criteria, competing against Finnish and Russian groups. They were successful and initiated work in January of 2001 (See Figure B.27). It is believed that their success was due in no small part to the extensive experience gained in the Canadian Beaufort Sea. Today in 2014, the Canadian group has had its contract extended four times and is still involved as this project has gone from exploration and delineation drilling into development. At the peak of the work there were up to 20 Canadian experts involved.

The development of the Kashagan field involves numerous platforms which are mostly retained islands. Again, the knowledge gained from the Beaufort Sea on ice interaction with wide structures in shallow water was a vital input. New and refined approaches used in this development have included: probabilistic ice load modelling on wide structures in shallow water, accounting for ice rubble; an ice rubble simulator to help in the positioning of ice barriers; methods for predicting and protecting against ice encroachment onto low-freeboard retained islands. An example of ice rubble build-up and ice encroachment are shown in Figures B.28 and B.29.

Another important aspect of the Kashagan development is pipelines both to shore and between the various production and processing islands. In all there will be over 1000km of pipelines. The sea floor is subject to frequent ice scouring (See Figure B.30). The Canadian team has played a vital role in determining safe burial depths for these lines to protect against ice interaction and damage. The approaches developed for Kashagan pipeline burial are considered state-of-the-art and will now be available for use in other Arctic regions (including Canada) as developments occur.

Lastly, Canadian experts have also been part of the teams involved in ice forecasting for the North Caspian, as well as acting as ice observers and advisors on the drilling rigs.

In summary, although the oil and gas developments in the North Caspian Sea are far from Canada and not strictly in the Arctic, this case history demonstrates how

Canadian expertise has been vital in enabling the developments. Also, it should be noted that Canadian experts successfully competed against Scandinavian and Russian expertise to be engaged. A rough estimate of revenues to Canadian companies from 2001 to 2014 is about $10 million. No Canadian government subsidies were involved in the successful bidding and implementation of this work. Nevertheless, the successful Canadian private company subcontracted significant work to the National Research Council and Memorial University (C-CORE).

Figure B.27: Canadians and Kazakh colleagues gathering ice data in the North Caspian Sea (Photo: K R Croasdale & Associates Ltd.)

Figure B.28: Ice rubble build-up against island and ice barriers
(Photos courtesy of Derek Mayne [top] and Rune Nilsen [bottom])

Figure B.29: Ice encroachment on low-freeboard structures
(Photo: Eric Lemee)

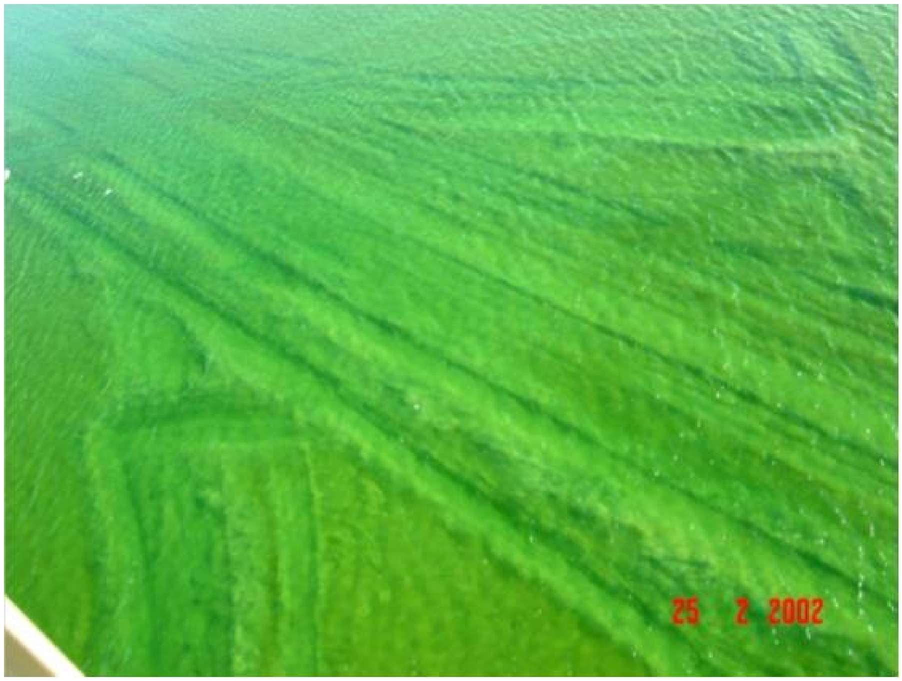


Figure B.30: Ice scouring of the sea floor, North Caspian Sea
(Photo: K R Croasdale & Associates Ltd.)

B.9 Shtokman Field: Iceberg loads for floater in Barents Sea

Introduction

Icebergs occur in many areas of the Arctic and subarctic: for example, West Greenland, east of Baffin Island and Labrador, on the Grand Banks, southeast Greenland, in the area neighbouring Svalbard, in the Barents Sea, and many other areas in the Russian arctic. Determination of iceberg loads for design of offshore facilities for exploration and especially for production is an important engineering task.

Engineering design aims at an appropriate balance between safety and economy. The use of probabilistic methods offers a solution that assists in obtaining such a balance. The specification of iceberg loads is guided by the ISO 19906 (2010) International Standard. The methodology used in the present study results in load-exceedance curves that can be used to determine design loads at a desired annual exceedance probability. In ISO 19906 the Extreme Level Ice Event (ELIE) and the Abnormal Level Ice Event (ALIE) for the design of an offshore platform are defined at annual exceedance probabilities of 10^{-2} and 10^{-4} respectively for L1 exposure.

Ice loads have been modelled using Monte Carlo methods, which take into account the underlying probabilistic distributions of the areal density of the ice feature (for example, the number of icebergs per 10,000 km^2), the size and mass of the features, their added mass, their velocity, eccentricity of the collision, forces from surrounding pack ice, compliance of the structure, and the strength of the ice. Previous work focussed on the Grand Banks, where two floating production platforms are now operating, the *Terra Nova* and *Sea Rose* FPSOs. Probabilistic methods were developed for these developments. Extension of the methodology for use in other areas is of considerable interest. An example is suggested in Figure B.31. The moderating influence of the North Atlantic Current results in conditions north of Norway and in the region of Svalbard that are similar in many respects to those offshore Newfoundland.

Modelling

The floating vessel considered in the analysis is illustrated in Figure B.32. The determination of iceberg design loads requires the following inputs for the simulations:

- areal density of the icebergs;
- size, velocity and shape of the icebergs;
- concurrent sea state and associated hydrodynamic effects on iceberg motion;
- eccentricity of loading to account for oblique impacts;
- global ice pressures developed on the basis of pressure-area relationships (derived from analysis of ship rams into hard, multi-year ice, or other relationships such as constant-pressure); and
- local ice pressures associated with the design loads (also derived from analysis of ship rams into hard multi-year ice, and a function of the duration of individual impact events and the frequency with which they occur).

In addition to these, detection and management of icebergs, and possible disconnection of the floating unit, are modelled.

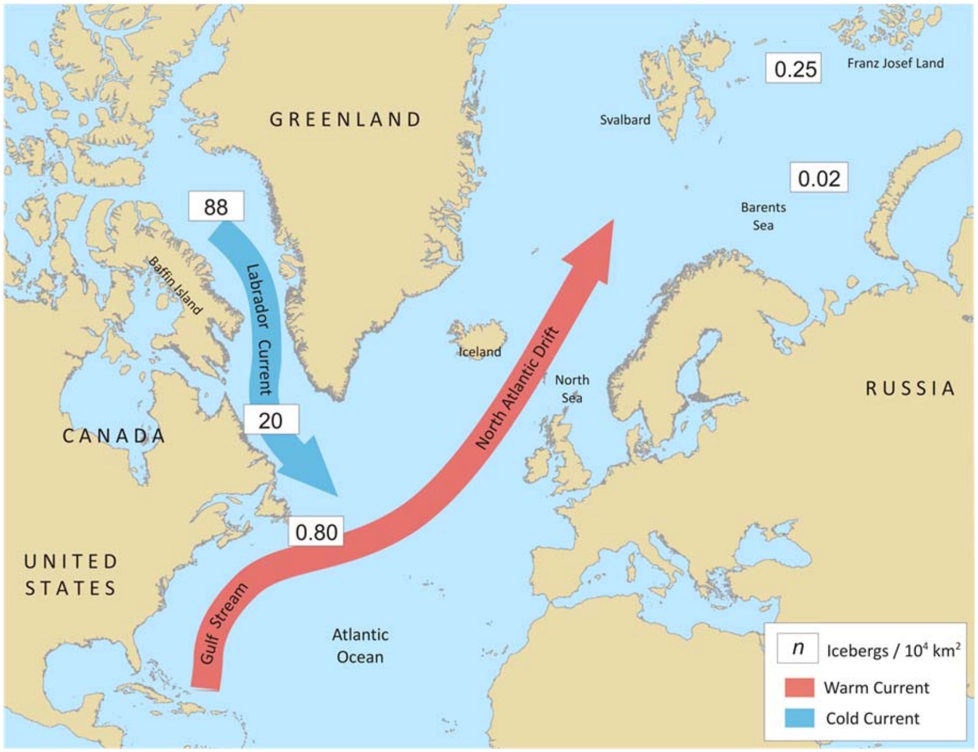


Figure B.31: Some geographical areas with approximate areal densities of icebergs (excluding bergy bits) per 10^4 km^2 indicated

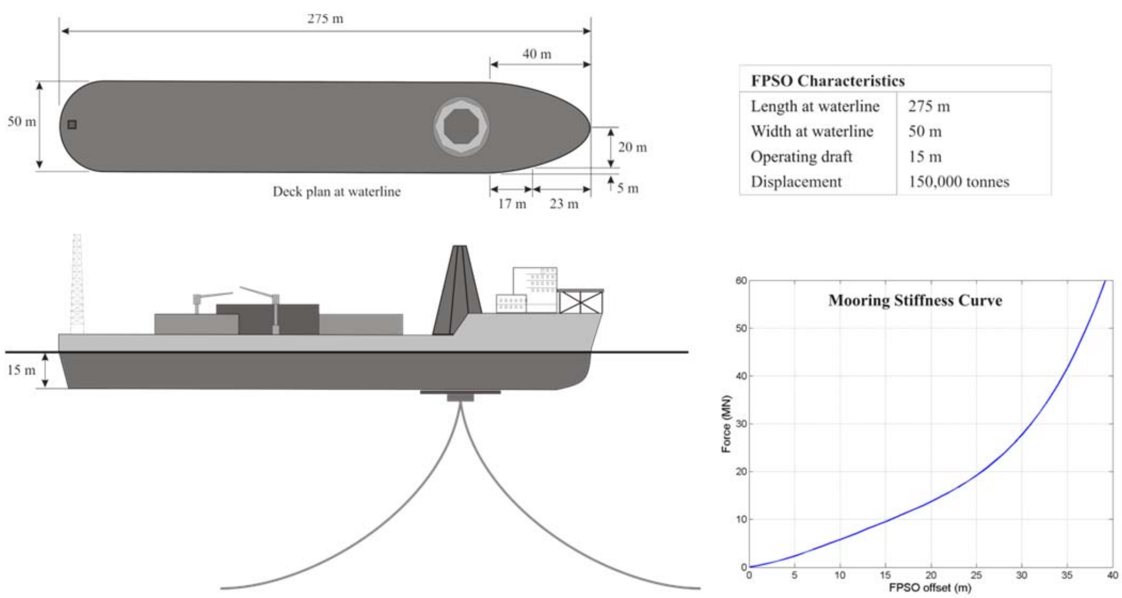


Figure B.32: Schematic of generic floating vessel used in study

(Jordaan et al., 2014)

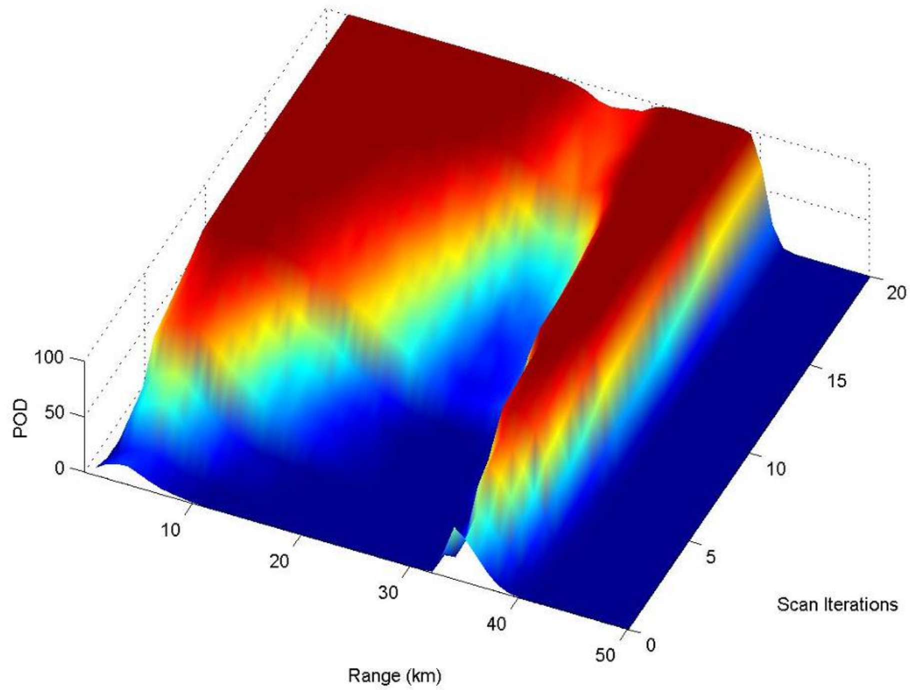


Figure B.33: Hibernia, X-Band detection of a 50m iceberg, 60 knot wind, 0 to 20 scans (Jordaan et al., 2014)

Models have been developed for iceberg management based on Canadian experience on the Grand Banks. Three key elements of iceberg management include detection, towing and disconnection. Detection performance is based on a special ice radar that is designed for small target detection in high seas. The system processes multiple scans to minimize clutter and false targets. Performance is based on the probability of detection (POD) of icebergs given iceberg size, sea state and range from the platform. Figure B.33 illustrates a typical input.

Without any management, the encounter frequency is about 5×10^{-3} per annum – less than the value at which extreme-level design should be considered, but certainly greater than the value used in the abnormal-level case. The dynamic analysis results in much reduced loads as compared to the values based on quasi-static analysis; for example, the quasi-static 10^{-3} and 10^{-4} exceedance loads of 10 and 150 MN reduce to about 5 and 40 MN respectively (without management). Iceberg management reduces the value at the 10^{-4} annual exceedance level to 26 MN.

Conclusion

A comprehensive methodology has been developed for obtaining design loads due to iceberg impacts, the original area of interest being the Grand Banks. In the present study, the methodology was applied to a region with much reduced areal densities of icebergs and a greater proportion of bergy bits. The Extreme-Level loads were found to be zero, but significant loads and local pressures have been found at the Abnormal Level (10^{-4} annual exceedance probability). Arrival rates, global forces (including the effects of dynamics of iceberg and vessel), mooring loads and local loads have been determined using the methodology outlined.

Appendix C: APOA Project listing from Glenbow Museum website

http://www.glenbow.org/collections/search/findingAids/archhtm/apoa.cfm#series6

Project 1: The Nutcracker ice strength tests. (1969-1972)

Project 2: Beaufort Sea: ice movement and current survey. (1970-1975)

Project 3: Ocean floor sampling, Beaufort Sea. (1970-1975)

Project 4: Geological analysis of ocean floor samples. (1970-1972)

Project 5: Study of Mackenzie Delta tundra disturbance. (1972)

Project 6: Summer ice reconnaissance. (1970)

Project 7: Cross-country vehicle study. (1970-1972)

Project 8: Arctic drilling guidelines. (1970-1974).
Includes minutes of the APOA Drilling Subcommittee, 1970)

Project 9: Large scale ice strength test: Phase II of "Nutcracker". (1970-1972)

Project 10: Testing with synthetic ice. (1970)

Project 11: Ornithological study, Mackenzie Delta. (1970-1972)

Project 12: All season exploratory drilling system: 0 to 200 feet of water. (1970-1975)

Project 13: Seasonal drilling from a barge. (1970-1975)

Project 14: Summer ice reconnaissance, Beaufort Sea. (1974-1975)

Project 15: Mackenzie Institute: travel costs for an Edmonton meeting. [empty folder]

Project 16: Theoretical analysis of ice failure. (1971-1972)

Project 17: Beaufort Sea pressure ridge and ice island scouring. (1971-1972)

Project 18: Arctic drilling concepts review. (1971)

Project 19: analysis of records showing sea bottom scouring. (1972)

Project 20: Cementing, casing, blowout procedures for DIAND. (1970-1974)

Project 20: cementing, casing, blowout procedures for DIAND: financial records. (1971-1973)

Project 21: Large wheeled low pressure vehicle. (1971-1974)

Project 22: Transportation of hydrocarbons from Arctic Islands. (1971)

Project 23: Beaufort Sea soil analysis. (1972)

Project 24: Arctic clothing research. (1971-1975) [Includes report.]

Project 25: Model test simulating ice on fixed structures. (1971-1975)

Project 26: Model test simulating ice on drilling barge. (1971)

Project 27: Coordination of Arctic environmental research. (1971-1972)

Project 28: Biological effects of oil in Arctic seawater. (1971-1974)

Project 29: Habakkuk: investigation of research on an artificial ice island. (1971-1972)

Project 30: Beaufort Sea exploratory drilling system. (1971-1975)

Project 31: aerial reconnaissance of ice, Beaufort Sea, 1971. (1972-1975)

Project 32: Beaufort Sea scour records, Phase II. (1972-1976)

Project 33: Landfast ice movement, Beaufort Sea. (1972-1973)

Project 34: Northern resources study. (1971-1974)

Project 34: Northern resources study: research plan. (1971)

Project 34: Northern oil and gas production related employment opportunities: the impact of Mackenzie Delta production: a study prepared for the Arctic Petroleum Operators Association / by Dennis Depape. (1973)

Project 35: Environmental study of the Baffin Bay-Davis Strait region. (1972-1975)

Project 36: Ice island destruction, Beaufort Sea. (1972-1975)

Project 37: Arctic environmental research: tundra and ecological studies on the Mackenzie Delta and Devon Island. (1971-1975)

Project 38: Testing of the effects on terrain by various types of vehicles. (1972-1974)

Project 39: Submarine pipeline study, offshore Mackenzie Delta. (1972-1976)

Project 40: Evaluation of mechanical properties of saline model ice. (1972-1974)

Project 41: Evaluation of the mechanical properties of Michel's model ice. (1972-1975)

Project 42: Survey of gravel, Mackenzie Delta. (1972-1974)

Project 43: Environmental impact assessment program, Mackenzie Delta. (1972)

Project 44: Photo reconnaissance and ice movement, Beaufort Sea. (1972)

Project 45: Arctic clothing study, Phase II. (1972-1975) [Includes report. Mould damage]

Project 46: Ice reconnaissance, Beaufort Sea, April 1972. (1972-1973) [Mould damage]

Project 47: Ice chipper evaluation tests. (1972-1973) [Mould damage]

Project 48: Study of vehicular traffic on the Mackenzie Delta tundra. (1972-1974 [Mould damage]

Project 49: Study of Arctic transportation equipment, Mackenzie Delta. (1972-1974) [Mould damage]

Project 50: Ice thickness measurement. (1972-1975) [Mould damage]

Project 51: ice movement in Beaufort Sea, 1972-1973. (1972-1973) [Mould damage]

Project 52: Measuring the crushing strength of ice. (1973-1974)

Project 53: Count of ice islands in Beaufort Sea, 1972. (1973)

Project 54: Ice geology of the southern Beaufort Sea. (1973-1977) [Mould damage]

Project 55: Arctic environmental research [Devon Island International Biological Program Project]. (1973-1974)

Project 56: Preparation of specifications for large Arctic truck. (1973-1974)

Project 57: Adfreeze study: effects of ice adhesion on a conical structure. (1973-1975)

Project 58: Task force re Northern Native job training. (1973-1974)

Project 59: Beaufort Sea scouring study, Phase III. (1973)

Project 60: Beaufort Sea summer ice testing. (1973-1974)

Project 61: Environmental impact assessment program, Mackenzie Delta, Phase II. ([1973-1974])

Project 62: Beaufort gas plan study, part 3. [empty folder]

Project 63: Arctic Insuitute of North America's Beaufort Sea symposium. (1973-1975)

Project 64: Ice mechanics and ice strengthening: 1973-74 Arctic field test program, Resolute Bay. (1973-1978)

Project 64: Vibration measurements made on an ice platform in the vicinity of Panarctic Hecla N-52 – for Sun Oil Company, Richardson, Texas by James E. Fix. (Garland, Tex.: Teledyne Geotech, 17 July 1974. [Technical report no. 74-4])

Project 64: Sea ice thickness determination using electromagnetic subsurface profiling. (Submitted to Sun Oil Company by A. Orange, K. Campbell & W. Corrieri. [North Billerica, Mass.: Geophysical Survey Systems, April 1973])

Project 64: Errata. (1976)

Project 64: Appendix no. I.1: raw deflection and water level data. (1974)

Project 64: Appendix no. I.2: reduced deflection and flood data tabulation. (1974)

Project 64: Appendix no. I.3: reduced deflection versus field graphs. (1974)

Project 64: Appendix no. I.4: reduced deflection versus time graphs. (1974)

Project 64: Appendix no. II.1: raw strain gauge data. (1974)

Project 64: Appendix no. III.1: ice core test tabulation. (1974)

Project 64: Appendix no. III.2: ice block temperature, core salinity and core density graphs. (1974)

Project 65: Small prototype cone test. (1974-1977)

Project 66: Ice crushing tests, 1973-74. (1974-1975)

Project 67: Ice movement, Beaufort Sea, 1973-74. (1974-1977)

Project 68: Properties of wax model ice ridges. (1974-1977)

Project 69: Analytic study of ice scour. (1974-1975)

Project 70: Wind/wave hindcast, Canadian Beaufort Sea. (1974)

Project 71: Northern Native job training task force, 1974. (1974-1975)

Project 72: Beaufort Sea Environmental Program: catalogue of project descriptions, catalogue of study reports. (1974-1977)

Project 72: Beaufort Sea Environmental Program. (Jan.-Mar. 1974)

Project 72: Beaufort Sea Environmental Program. (Apr.-July 1974)

Project 72: Beaufort Sea Environmental Program. (Aug.-Sept. 1974)

Project 72: Beaufort Sea Environmental Program. (Oct.-Dec. 1974)

Project 72: Beaufort Sea Environmental Program. (Jan.-Apr. 1975)

Project 72: Beaufort Sea Environmental Program. (June-Sept. 1975)

Project 72: Beaufort Sea Environmental Program. (Oct.-Dec. 1975)

Project 72: Beaufort Sea Environmental Program. (1976)

Project 72: Beaufort Sea Environmental Program. (1977)

Project 72: Beaufort Sea Environmental Program: Investigators' Conference and Sea Drilling Seminar. (Nove. 1974 - Jan. 1975)

Project 72: Beaufort Sea Environmental Program: Windup Conference. (Dec. 1975 - Jan. 1975)

Project 72: Beaufort Sea Environmental Program. Public Interface Program. (1974-1976)

Project 73: Research program on pollution from drilling fluids. (1974-1979)

Project 73: Report on containment and disposal of drilling fluids in the Northwest Territories – for the Arctic Petroleum Operators Association and the Government of Canada. ([S.n.]: Dames & Moore, March 1974)

Project 74: Banks Island development: environmental considerations. (1974-1975)

Project 75: Field study of first-year ice pressure ridges. (1974-1977)

Project 76: Summer environmental studies: East Mackenzie Bay, Mackenzie Delta. (1974)

Project 77: Modelling of small cone prototype tests. (1974-1975)

Project 78: Environmental data gathering program: Baffin Bay, Davis Strait, and Arctic Islands. (1974-1977)

Project 79: Arctic Island ice movement study, 1974-1975. (1974-1977)

Project 79: Analysis of oceanographic data for APOA Project No. 79 - prepared for Panarctic Oils Ltd., Calgary, Alberta. (Calgary: Beak Consultants, Apr. 1976)

Project 80: Development of a semi-submersible drilling system for the Arctic offshore area. (1974-1975)

Project 81: Ice mechanics 1974-75, Arctic field test program, Resolute Bay. (1974-1975)

Project 82: Small prototype cone test, Phase II. (1972-1977)

Project 83: Landfast ice movement in the Beaufort Sea, 1974-75. (1975-1977)

Project 84: In-situ ice property measurement in the Beaufort Sea. (1975-1977)

Project 85: Adfreeze on conical structures. (1975-1977)

Project 86: Study of ridge/cone interaction. (1975)

Project 87: Computerize a mathematical model of ice/cone interaction. (1975-1977)

Project 88: Ya Ya Lake gravel testing program. (1975)

Project 89: Thickness of multi-year pressure ridges. (1975-1979)

Project 90: Mobile Arctic Ice Chipper. (1975)

Project 91: Strength of multi-year pressure ridges. (1975)

Project 92: Arctic Islands sea ice movement analysis from ice reconnaissance and satellite imagery data: 1974-1977)

Project 93: High speed ice crushing tests. (1975-1977)

Project 94: Development of a semi-submersible drilling system for the Arctic offshore area, Phase II. (1977)

Project 95: Arctic Islands ice movement study, 1975-1976. (1975-1977)

Project 96: Statistical study of the winter ice thickness distribution in the Arctic Islands from seismic data (1971 to 1975). (1975-1977)

Project 97: Full scale tests of the Lockheed Clean Sweep Arctic Boat R2003 oil recovery system. (1975)

Project 98: Arctic Science and Technology Information System (ASTIS). (1972-1977)

Project 98: Arctic Science and Technology Information System (ASTIS). (1978-1982)

Project 98: Arctic Science and Technology Information System (ASTIS): letters of agreement. (1975-1979)

Project 99: Ice island count, southern Beaufort Sea, 1974-1976. (1975-1977)

Project 100: Test programme to evaluate a new concept of oil containment boom for use in ice infested waters. (1975)

Project 101: Field testing of the Mobile Ice Chipper II. (1975-1976)

Project 102: Multi-year pressure ridge study, Queen Elizabeth Islands. (1976)

Project 103: Interaction between ice sheets and wide structures. (1976-1977)

Project 104: Measurement of ice pressure on artificial islands. (1976-1977)

Project 105: In-situ pressure measurements around artificial islands in southern Beaufort Sea, Phase II. (1976-1977)

Project 106: Continuous crushing of a ice island by a circular indenter. (1976-1977)

Project 107: Burning oil on water in an ice environment. (1976-1977)

Project 108: Feasibility and limits of burning an oil blowout plume. (1976)

Project 109: Model ice pile-up and ride-up on islands. (1976-1977)

Project 110: Conical and cylindrical gravity structures for southern Beaufort Sea. (1976-1977)

Project 111: Evaluation of ice defence systems for artificial islands. (1976-1977)

Project 112: Geometry of a continuous multi-year pressure ridge. (1976)

Project 113: Passage into Beaufort Sea via Point Barrow. (1976-1977)

Project 114: Preliminary tests of bird-scare devices in the Beaufort Sea. (1976-1977)

Project 115: Polar bear research. (1976-1977)

Project 116: Drilling from ships in shorefast ice. (1976)

Project 117: Statistical study of late winter ice distribution in the Arctic Islands from seismic data. (1976)

Project 118: Arctic Islands winter ice movement study. (1976)

Project 119: Remote detection of oil in/under ice. (1976-1977)

Project 120: Safe ice detector: Project SID. (1976-1979)

Project 121: Multi-year pressure ridge study, Arctic Islands. (1977)

Project 122: In-situ ice pressure measurements, 1976-1977. (1976-1977)

Project 123: Continuous crushing of ice, 1976-77. (1976-1977)

Project 124: Study of ice pile-up. (1976-1977)

Project 125: Experimental ridge CRI interaction, 1976-77. (1976-1977)

Project 126: Biological literature review of Davis Strait. (1976-1977)

Project 127: Davis Strait winter biological sampling analysis and investigations. (1977)

Project 128: Davis Strait pack ice studies, 1976-77. (1977)

Project 129: Davis Strait ocean current measurements and analysis, 1976. (1977)

Project 130: Davis Strait studies of production structures in the southern Beaufort Sea. (1971)

Project 131: Feasibility study of a bottom mounted under ice profiling system. (1977)

Project 132: Instrumentation of drilling fluid sumps. (1977-1979)

Project 133: Investigation of sea-bed scouring in the Beaufort Sea, phase III. (1977-1978)

Project 134: Biological and oceanographic study, Davis Strait area. (1977)

Project 135: Biological surveys, Davis Strait, 1976. (1977)

Project 136: Shoreline study of Beaufort Sea, Komakuk Beach to Baillie Islands. (1977-1978)

Project 137: Tests of ignition and herding devices for burning oil on ice [project deferred, see Project 141])

Project 138: Davis Strait environmental propgram, second half 1977. (1977)

Project 139: Development of an ice monitoring system in the Beaufort Sea. (1977)

Project 140: Davis Strait ice pack incursion studies, 1977/78. (1977)

Project 141: Ignition and burning of crude oil on water pools under Arctic springtime conditions. (1977)

Project 142: Statistical study of late winter ice thickness in the Arctic Islands from seismic data, 1977. (1977-1978)

Project 143: Model experiments to determine the forces and behaviour of moving ice fields against drilling caissons. (1977-1978)

Project 144: Caisson retained island and ice ridge interaction studies, 1977/78. (1978)

Project 145: Caisson retained island. (1978)

Project 146: Davis Strait biological programme. (1978)

Project 147: Ice keel profiling in the Beaufort Sea. (1978-1980)

Project 148: Studies of continuous crushing of ice [empty folder])

Project 149: Oilspill and iceberg studies conducted for an environmental impact statement for Davis Strait. (1978)

Project 150: Ice scour model tests. (1978)

Project 151: Analysis of 1978 Beaufort Sea side scan sonar mosaics for recent sea bottom scouring. (1978)

Project 152: Beaufort sea well completions in permafrost. (1978)

Project 153: In-situ gas hydrates survey. (1978-1979)

Project 154: High resolution ice tracking system: Beaufort Sea, Phases II and III: buoy construction and deployment. [empty folder]

Project 155: Davis Strait pack ice characterization. [empty folder]

Project 156: Ice island studies, 1978-79. (1979)

Project 157: Trace metal characteristics in barite for drilling operations. (1979)

Project 158: Beaufort Sea repetitive scour mapping, 1979. [empty folder]

Project 159: Portable oil burner. (1979)

Project 160: Fireproof boom development. (1979)

Project 161: Bacterial degradation study. (1979)

Project 162: Under ice bubbler test. [empty folder]

Project 163: Literature study on bird deterrent techniques. (1979)

Project 164: Air deployable igniter tests. (1979)

Project 165: Air deployable igniter improvements. (1979)

Project 166: In-situ combustion of oil slicks against edges. (1979)

Project 167: Mechanical oil recovery systems in ice. (1979)

Project 168: Polar bear detector and deterrent devices. [empty folder]

Project 169: Oil and gas under Beaufort Sea study. [empty folder]

Project 170: Investigation of grounded rubble piles in the Beaufort Sea. (1979-1981)

Project 171: Investigation of ice conditions and ice behaviour around Issungnak. (1980)

Project 172: Davis Strait weather/seastate buoy program and forecasting studies. (1980)

Project 173: Ecology of the southern Beaufort Sea and Mackenzie River Delta: an annotated bibliography. (1980)

Project 174: Statistical study of late winter ice thickness distribution in the Arctic Islands from seismic data (1978-1980). (1980-1982)

Project 175: Development of an ice thickness profiler using acoustics. (1980)

Project 176: Beaufort Sea seismicity measurement program. (1980)

Project 177: Ice rubble model tests. ([1980])

Project 178: Bridge-building model tests. (1980)

Project 179: Preliminary assessment of seismic forces and seismicity of the Canadian Beaufort Sea and preliminary investigation of potential behaviour of sand islands during earthquakes. (1980)

Project 180: Ice forces on Hans Island, 1980. (1981)
[Includes report]

Project 181: Ice forces on Hans Island, 1981. (1981)

Project 182: Videotape of the Canadian Beaufort Sea coast from the Alaska/Yukon border to the Baillie Islands. (1981)

Project 183: Beaufort Sea "GEOPOC" study (geotechnical evaluation of permafrost on casings). (1982)

Project 184: Low-cost side-looking airborne radar for sea ice reconnaissance in the Beaufort Sea. (1981)

Project 185: Natural ice rubble studies. (1981)

Project 186: Ice rubble model test, part 2. (1981)

Project 187: Surface disposal of drilling fluids in permafrost regions. (1982)

Project 188: Computer-assisted learning oil spill response training. (1981-1984)

Project 189: Mitsui's Archimedean screw tractor (AST 002) in the Canadian Beaufort Sea. (1981-1982)

[Projects 190-195 files missing]

Project 196: Analysis of accidents in offshore operations where hydrocarbons were lost. (1982)

Project 197: Tarsuit Island research program. ([1982])

Project 198: Tarsuit Island research program, 1982-83. (1982)

Project 199: Multi-year ice floe survey, 1982. (1982)

Project 200: Multi-year ice test program. (1982)

Project 201: Multi-year hummock field and floe-size survey. (1982)

Project 202: Ice forces on Hans Island. (1982-1983)

[Project 203 file missing]

Projects 204-211: Beaufort Sea production strategic engineering studies for 1983 – for Dome Petroleum Limited. (1982)

Project 212: Dispersants: areas of application for the Beaufort Sea. (1983)

[Project 213 file missing]

Project 214: Upward-looking ice profiler study. (1983)

[Project 215 file missing]

Projects 216-219: Beaufort Sea production strategic engineering projects for 1984 – for Dome Petroleum Limited. (1984)

[Project 220 file missing]

Project 221: Arctic escape system, phase II. (1985-1986)

[Project 222 file missing]

Appendix D: Inventory of Canadian Centres Oriented towards Northern Research

D.1 ArcticNet

http://www.arcticnet.ulaval.ca/

General description: ArcticNet is a Network of Centres of Excellence of Canada that brings together scientists and managers in the natural, human health and social sciences with their partners from Inuit organizations, northern communities, federal and provincial agencies and the private sector. The objective of ArcticNet is to study the impacts of climate change and modernization in the coastal Canadian Arctic. Over 145 ArcticNet researchers from 30 Canadian Universities, 8 federal and 11 provincial agencies and departments collaborate with research teams in Denmark, Finland, France, Greenland, Japan, Norway, Poland, Russia, Spain, Sweden, the United Kingdom and the USA. ArcticNet is conducting Integrated Regional Impact Studies on societies and on marine and terrestrial coastal ecosystems in the Canadian High Arctic, in the Eastern Canadian Arctic, and in Hudson Bay. In addition to work conducted in northern communities, ArcticNet researchers from various fields use the Canadian research icebreaker *CCGS Amundsen* to access the vast expanses of the coastal Arctic. This integrated research offers a unique multi-disciplinary and cross-sectorial environment to train the next generation of specialists, from north and south, needed to manage the Canadian Arctic of tomorrow. The ArcticNet Administrative Centre is hosted at Université Laval, Quebec City, Canada.

D.2 Centre for the North (CFN)

http://www.centreforthenorth.ca/

The Centre for the North is an initiative of the Conference Board of Canada (CBC) that began in 2009. The mandate of CBC, which CFN follows, is included below. The goal is to bring Aboriginal leaders, businesses, governments and community advocates together to identify challenges and opportunities and to decide how those challenges can be met.

At present there is a staff of five: one director, three researchers and one general staffer. They:

- deliver cutting-edge research based on three foundational themes of thriving communities, economic development and sovereignty and security in the North;

- examine issues from a Northern perspective, seek to maximize Northern engagement, and prioritize Northern interests;

- create unique networking opportunities with Northern representatives from government, industry, academia and Aboriginal groups - the only roundtable in Canada to provide this balanced matrix of dialogue;
- focus on delivering practical solutions to the wide ranging socio-economic challenges facing Canada's Northern communities;
- cover the territorial North as well as the northern regions of seven provinces; and
- are supported by a roundtable of 50 members that determine and review the Centre's research projects.

CFN has several major research projects underway:

- The Role of the Public Sector in Northern Governance;
- Connectivity Issues in Canada's North;
- Aboriginal Child and Youth Wellness;
- Energy in Canada's North; and
- Managing the Impacts of Economic Development in Northern Marine Waters.

Conference Board of Canada

About CBC:

- The foremost independent, not-for-profit applied research organization in Canada.
- Objective and non-partisan. We do not lobby for specific interests.
- Funded exclusively through the fees we charge for services to the private and public sectors.
- Experts in running conferences but also at conducting, publishing, and disseminating research; helping people network; developing individual leadership skills; and building organizational capacity.
- Specialists in economic trends, as well as organizational performance and public policy issues.
- Not a government department or agency, although we are often hired to provide services for all levels of government.

- Independent from, but affiliated with, The Conference Board, Inc. of New York, which serves nearly 2,000 companies in 60 nations and has offices in Brussels and Hong Kong

Mission: The Conference Board builds leadership capacity for a better Canada by creating and sharing insights on economic trends, public policy and organizational performance.

D.3 Canadian Polar Commission (Government of Canada)

http://www.polarcom.gc.ca/principal/eng/content/contact-us

Established in 1991, the Canadian Polar Commission has responsibility for: monitoring, promoting and disseminating knowledge of the polar regions; contributing to public awareness of the importance of polar science to Canada; enhancing Canada's international profile as a circumpolar nation; and recommending polar science policy direction to government.

In carrying out its mandate, the Commission hosts conferences and workshops, publishes information on subjects of relevance to polar research, and works closely with other governmental and non-governmental agencies to promote and support Canadian study of the polar regions.

The Canadian Polar Commission's mandate requires it to:

- monitor polar knowledge in Canada and around the world;
- work with Canadian and international institutions to determine scientific and other priorities;
- encourage support for Canadian polar research;
- communicate polar research information to Canadians; and
- foster international co-operation in the advancement of polar knowledge.

D.4 Canadian High Arctic Research Station (CHARS)

http://www.science.gc.ca/default.asp?lang=En&n=74E65368-1

The Canadian High Arctic Research Station (CHARS) will provide a world-class hub for science and technology in Canada's North that complements and anchors the network of smaller regional facilities across the North. The new Station will provide a suite of services for science and technology in Canada's North, including a technology development centre, traditional knowledge centre and advanced laboratories.

The Station will attract international scientists to work in Canada and will strengthen Canada's leadership position in Arctic research. Northerners are engaging in cutting-edge science and technology to address their needs in a changing North. This Station will be built by Canadians, in Canada's Arctic, and will be there to serve the world. The Canadian High Arctic Research Station is located in Cambridge Bay, Nunavut.

Objectives:

Mobilize Arctic science and technology:

- to develop and diversify the economy in Canada's Arctic;
- to support the effective stewardship of Canada's Arctic lands, waters, and resources;
- to create a hub for scientific activity in Canada's vast and diverse Arctic;
- to promote self-sufficient, vibrant, and healthy Northern communities;
- to inspire and build capacity through training, education, and outreach; and
- to enhance Canada's visible presence in the Arctic and strengthen Canada's leadership on Arctic issues.

Principles:

- Address pressing issues in Canada's Arctic by conducting world-class research and delivering excellent and relevant science and technology
- Complement the network of Arctic expertise and facilities across Canada's Arctic and the whole of the country
- Promote partnerships and collaboration among the private, Aboriginal, academic, and public sectors both domestically and internationally
- Work with Aboriginal peoples of Canada's Arctic and recognize the importance of traditional knowledge in advancing Arctic research
- Integrate across disciplines and across activities - from problem identification, through research and development, to solutions
- Ensure effective use of data, information, and technology through open and timely access and knowledge application
- Be a world leader in green technologies for the Arctic

Engineering relevance: the Science and Technology Plan for 2015 to 2019 has been announced with Call for Proposls on two themes; the first is baseline monitoring of environmental and health factors, and the second on tools to use baseline data, taking into accoutn climate change, for decision making in the context of resoutrce development focused on specific geographic areas. The results of these projects will have engineering application.

http://www.science.gc.ca/default.asp?lang=En&n=078AA8A0-1

D.5 C-CORE, LOOKNorth & CARD (centres within C-CORE)

Established in 1975 as the ***Centre for Cold Ocean Resources Engineering*** to address challenges facing oil & gas development offshore Newfoundland & Labrador and other ice-prone regions, C-CORE is now a multi-disciplinary organization with world-leading capability in **Remote Sensing**, **Ice Engineering** and **Geotechnical Engineering**.

Headquartered in Canada at St John's NL, with offices in Halifax, Ottawa and Calgary, C-CORE maintains a close collaborative relationship with Memorial University, with access to its extensive facilities, diverse academic expertise and $100 million research portfolio.

C-CORE is also home to LOOKNorth, a Canadian Centre of Excellence for remote sensing innovation to support northern resource development, and the Centre for Arctic Resource Development (CARD).

LOOKNorth: LOOKNorth is a Canadian Centre of Excellence for Commercialization and Research established by C-CORE, an international leader in R&D for harsh environments. Headquarted in C-CORE's facilities at Memorial University (St. John's, NL), LOOKNorth's purpose, in collaboration with a broad network of industry, business and research partners, is to validate and commercialize remote sensing (RS) technologies that support responsible, sustainable resource development in Canada's North.

LOOKNorth focuses on natural resource industries (particularly oil & gas, mining and hydro-power), as well as the transportation sector related to these. It aims to leverage RS technologies and derived data products/services that can provide information to overcome knowledge gaps and positively impact project economics, accelerate permitting and improve operational safety.

CARD: The Centre for Arctic Resource Development (CARD) serves as focal point for planning, coordinating and conducting research to fill gaps in the knowledge, technology, methodology and training needed to remove these barriers. The Centre focuses its efforts on key barriers identified by the broader research community and various sectors of the oil and gas industry. Its research programs are organized into core areas of Ice Mechanics, Ice Management and Station-Keeping in Ice, and are related through the common activities of Floating System Modelling and Large-Scale Experiments.

D.6 Canadian Network of Northern Research Operators

http://www.polarcom.gc.ca/index.php?page=canadian-network-of-northern-research-operators-cnnro

The Canadian Network of Northern Research Operators (CNNRO) was formed over five years ago to facilitate collaboration and the exchange of information among all stakeholders who share an interest in infrastructure and logistics to support research in northern Canada.

Its members meet annually to share best practices and help each other address some of their common challenges.

Its main activities include maintaining an on-line registry of practical information about the research facilities and promoting their services to the northern research community.

Engineering relevance: logistic support for field work, could complement PCSP

D.7 Arctic Institute of North America (at U of Calgary)

http://arctic.ucalgary.ca/

Created by an Act of Parliament in 1945, the Arctic Institute of North America is a non-profit membership organization and a multi-disciplinary research institute of the University of Calgary.

The institute's mandate is to advance the study of the North American and circumpolar Arctic through the natural and social sciences, the arts and humanities and to acquire, preserve and disseminate information on physical, environmental and social conditions in the North.

Engineering relevance: great store of documents, studies focussed mainly on environmental and social science issue.

D.8 NRC Arctic Program

Work in progress; northern resource development (oil and gas), marine transportation and housing.

D.9 Program of Energy Research and Development (PERD)

http://www.nrcan.gc.ca/energy/science/programs-funding/1603

The Program of Energy Research and Development (PERD) is a federal interdepartmental program operated by Natural Resources Canada (NRCan). PERD funds research and development designed to ensure a sustainable energy future for Canada in the best interests of both our economy and our environment.

Please note that PERD only provides funding to federal departments and agencies. It is not a general funding or grant program for companies, associations or individuals.

These departments and agencies may collaborate with the private sector and other public and private agencies.

Offshore Environmental Factors: determine offshore environmental factors for regulatory, design, safety and economic purposes (East Coast oriented).

Sub-programs:

- Wind & Wave Hindcasting & Forecasting
- Sea Ice & Iceberg Detection & Forecasting
- Ocean Current Measurement & Circulation Modelling
- Ice-Structure Interaction Research & Standard Setting
- Seabed Stability Research & Development

Northern Regulatory Requirements: Supports regulatory processes and minimizes environmental and safety risks for northern oil and gas development.

Sub-programs:

- Biophysical Environment
- Environmental Impacts
- Ice Engineering & Design

Marine Transportation & Safety: Carries out R&D in aid of regulatory requirements for the safe and efficient transportation of oil and gas by tankers, and personnel safety standards in offshore operations.

Sub-programs:

- Offshore Personnel Safety
- Marine Operations
- Ship Safety

Regulatory Requirements for Drilling Wastes & Production Waste; Remediation of Accidental Offshore Discharges and Spills

Sub-programs:

- Drilling Wastes
- Produced Water
- Remediation of Accidental Offshore Discharges and Spills

D.10 Polar Continental Shelf Program (PCSP)

http://www.nrcan.gc.ca/earth-sciences/products-services/polar-shelf-services/11617

In accordance with Natural Resources Canada's legislative authorities, the Polar Continental Shelf Program (PCSP) coordinates field logistics in support of advancing scientific knowledge and management of Canada's lands and natural resources. As a national service delivery organization, PCSP coordinates logistics for Canadian government agencies, provincial and territorial government agencies, northern organizations, universities and independent groups conducting research in Canada's North, and through this work, PCSP directly contributes to the exercise of Canadian arctic sovereignty.

The Polar Continental Shelf Program's mission is to provide safe, efficient and cost-effective logistics services in support of Government priorities and economic prosperity.

D.11 Beaufort Regional Environment Assessment (BREA) 2011-14

http://www.aadnc-aandc.gc.ca/eng/1310583424493/1310583559732

The Beaufort Regional Environmental Assessment (BREA) is a four year (2011 to 2015), multi-stakeholder initiative that is sponsoring regional environmental and socio-economic research to assist in preparing all parties, including the federal government and local communities, to respond to new investments in oil and gas in the Beaufort Sea. The proposal was initiated and is supported by partners from the Inuvialuit Settlement Region, territorial and federal governments, the oil and gas private sector and academia.

Through multi-stakeholder committees, the BREA is building a regional knowledge base to inform regulatory processes and project-specific environmental assessments related to oil and gas activity in the Beaufort Basin. This is being achieved through the implementation of a targeted research program and working groups that are addressing key regional issues including cumulative effects assessment, information management, regional waste management, oil spill preparedness and response, socio-economic indicators, and climate change.

The initiative is aligned with the Northern Strategy and directly supports the priorities of protecting our environmental heritage and promoting safe and sustainable social and economic development in Canada's North.

For more information, visit: www.BeaufortREA.ca

D.12 Environmental Studies Research Funds (ESRF), CAPP supported

http://www.esrfunds.org/abopro_e.php

Profile

The Environmental Studies Research Funds (ESRF) is a research program which sponsors environmental and social studies. It is designed to assist in the decision-making process related to oil and gas exploration and development on Canada's frontier lands. The ESRF program, initiated in 1983, receives its legislative mandate through the *Canada Petroleum Resources Act* (CPRA), which was proclaimed in February 1987. As well the *Canada-Newfoundland Atlantic Accord Implementation Act* and the *Canada-Nova Scotia Offshore Petroleum Resources Accord Implementation Act* provide legislative direction. The funding for the ESRF is provided through levies on frontier lands paid by interested holders such as the oil and gas companies. The ESRF is directed by a joint government/industry/public Management Board and is administered by a small secretariat which resides in the Office of Energy Research and Development, Natural Resources Canada, Ottawa, Ontario.

Structure and Operation of the Funds

The purpose of the ESRF is to finance environmental and social studies pertaining to the manner in which and to the terms and conditions under which petroleum exploration, development, and production activities on frontier lands should be conducted. Frontier lands, defined as those areas where Canada has the right to dispose of or exploit the natural resources, are situated in the offshore areas of Canada's East and West Coasts and the areas north of 60 degrees. Environment is interpreted in the broadest possible sense and extends from the physical environment and biological environment issues to socio-economic issues.

The ESRF are directed by a 12-member Management Board which has representation from the federal government (4), the Canada-Newfoundland Offshore Petroleum Board (1), the Canada-Nova Scotia Offshore Petroleum Board (1), the oil and gas industry (4), and the general public (2). Robert Steedman, Professional Leader of Environment at the National Energy Board (NEB) is the current chairman of the ESRF Management Board. The ESRF is administered by a small secretariat within Natural Resources Canada.

The ESRF Management Board takes a hands-on approach to the conduct of the business of the ESRF. On behalf of the Minister of Natural Resources and the Minister of Indian Affairs and Northern Development, the Management Board sets priorities for study topics, determines the program budget, and facilitates the development of study proposals. The ESRF provides a forum for industry and government to develop a common knowledge base and to jointly design a focused study program which addresses the needs of both groups and avoids a repetition of effort and expense.

The program operates on a calendar-year basis. The Management Board has traditionally met on a semi-annual basis; however, the frequency of meetings is adjusted as circumstances dictate. The Management Board assesses the information requirements of government and industry to determine study subject priorities for which a study program for the coming year is developed. The budget to support the study program and administrative costs form the basis for the calculation of the levy rate schedule. The budget and levy rates are submitted to the Ministers for approval by 1 November of each year. The projects under the study program are initiated following the collection of the levies, which generally occurs in the first quarter of the calendar year.

Appendix E: Review of Recent Reports

The focus of the report is engineering in Canada's northern oceans and waters. In order to deal with this adequately, there is a chapter on northern resources, as mining activities will almost inevitably require access by sea. In the same vein, reviews in the present section include aspects which are land-based yet are relevant to northern development, such as road and rail.

E.1 CFN *Changing Tides*: Economic Development in Canada's Northern Marine Waters (Fournier, S. and Caron-Vuotari, M., 2013)

The report emphasizes that Canada's northern marine waters represent one of the world's last natural resource frontiers. Development will hinge on four factors: climate change, infrastructure, emergency response and SAR, and commodity prices. It summarizes renewed interest in oil and gas exploration in the Beaufort Sea, and recent offshore licenses in deeper waters in Beaufort Sea.

With regard to climate change, the report considers that this will improve the accessibility of northern marine waters. It does emphasize spatial and temporal variation of temperature changes. For example, the western Canadian Arctic has seen temperatures rise by as much as 2.2° C over the past 50 years, almost 1° C higher than the average increase for the country as a whole. The average increase in temperature in Canada has been above global averages. The strongest warming trends between were in the far North of Canada. Referring to Figure E.1, these were the Arctic Tundra, Arctic Mountains and Fjords, Mackenzie District, and Yukon and North British Columbia climatic regions. Some areas saw little increase in temperature.

In the past few decades there has been an increase in overall shipping traffic throughout Canada's Northern marine waters, especially since 2006. Natural resources activity, particularly mining projects, is partly responsible for the increase, as are resupply services to Northern communities. But tourism and fishing activities are also playing a role.

Less ice due to warming means increased accessibility with regard to shipping. The situation is correctly described as "complex." Changes to the type of ice that will be found in Northern waters are important. Old ice may be present. Powerful ice-breakers are required to penetrate and navigate through multi-year ice, whereas less robust vessels can operate in first-year ice, although this ice may become ridged and more difficult to penetrate.

An important impact is permafrost reduction, occurring in parts of Yukon, the Beaufort and Mackenzie regions of the Northwest Territories, and the region surrounding James Bay on the west side of Hudson Bay. Shorter winters and higher average temperatures will reduce the amount of time that ice roads can safely be used, with a reduction in the length of the transportation window. This can mean significant losses for impacted industries and communities. Ice roads have become increasingly unreliable over the past few decades in certain parts of the North. Permafrost reduction can affect rail lines and the use of railroads may become less attractive than marine transportation.

Currently, the infrastructure in and around Northern Canadian waters is not sufficient for broad-based economic development. The only deepwater port in the Arctic at present is at Churchill, Manitoba. One is planned by the Canadian government for Nanisivik, expanding the facility developed for the Nanisivik mine. Search-and-rescue (SAR) facilities along with disaster response capability are seen to be inadequate.

Development of industry and commercial enterprises can be a driver for the development of facilities. A boom-and-bust issue is associated with this: facilities can be built for a particular development, used, and then not remain (or not be suitable) for community use.

The report gives examples of approved and plausible projects in Canada's North include:

- The publicly funded Mackenzie all-weather high- way in N.W.T. that would connect the port at Tuktoyaktuk to Inuvik and, ultimately, to Wrigley;

- Government of Canada investment in a refuelling and docking station for military and coastguard vessels (although originally intended as a more expansive deepwater port facility) at Nanisivik;

- Possible private sector investment in a deepwater port and road at the head of Bathurst Inlet for mining operations (zinc and gold) in the region.

- Port of Churchill could see its role expanded through the provision of services to communities and mining operations along the Kivalliq coast and in meeting freight demands for Nunavut in general.

Conclusions to the report are summarized as follows:

- A need for greater collaboration and integration with respect to decision-making and governance on issues relevant to economic development in the marine waters of Canada's North. By sharing knowledge and expertise, stakeholders can remove or reduce incomplete information as well as capacity constraints.

- Leveraging public and private sector resources for infrastructure projects, for instance, is one way of addressing the infrastructure deficit in Canada's North. Similarly, infrastructure projects should try to be leveraged so that they target multiple objectives.

- Uncertainty presents a problem that has to be dealt with.

- Emphasis on safety and safety culture in northern development. "Northerners, governments, and industry must emphasize risk reduction and building a culture of safety in all areas of potential economic development."

- "The way that the risks and benefits of economic development are weighted and managed must make sense to Northerners, keep their interests front and centre, and effectively capture the Northern context."

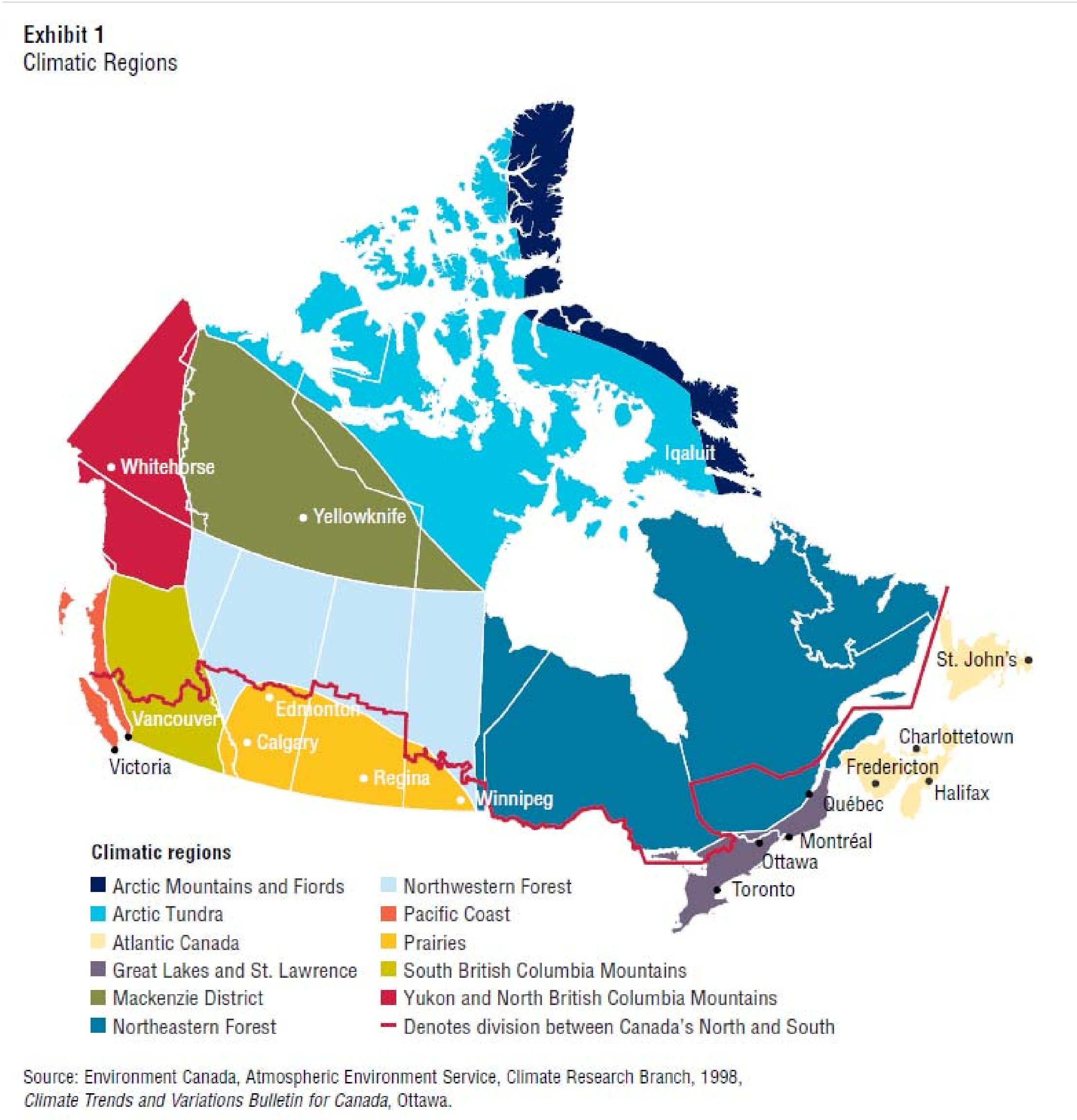


Figure E.1: Climatic Regions of Canada

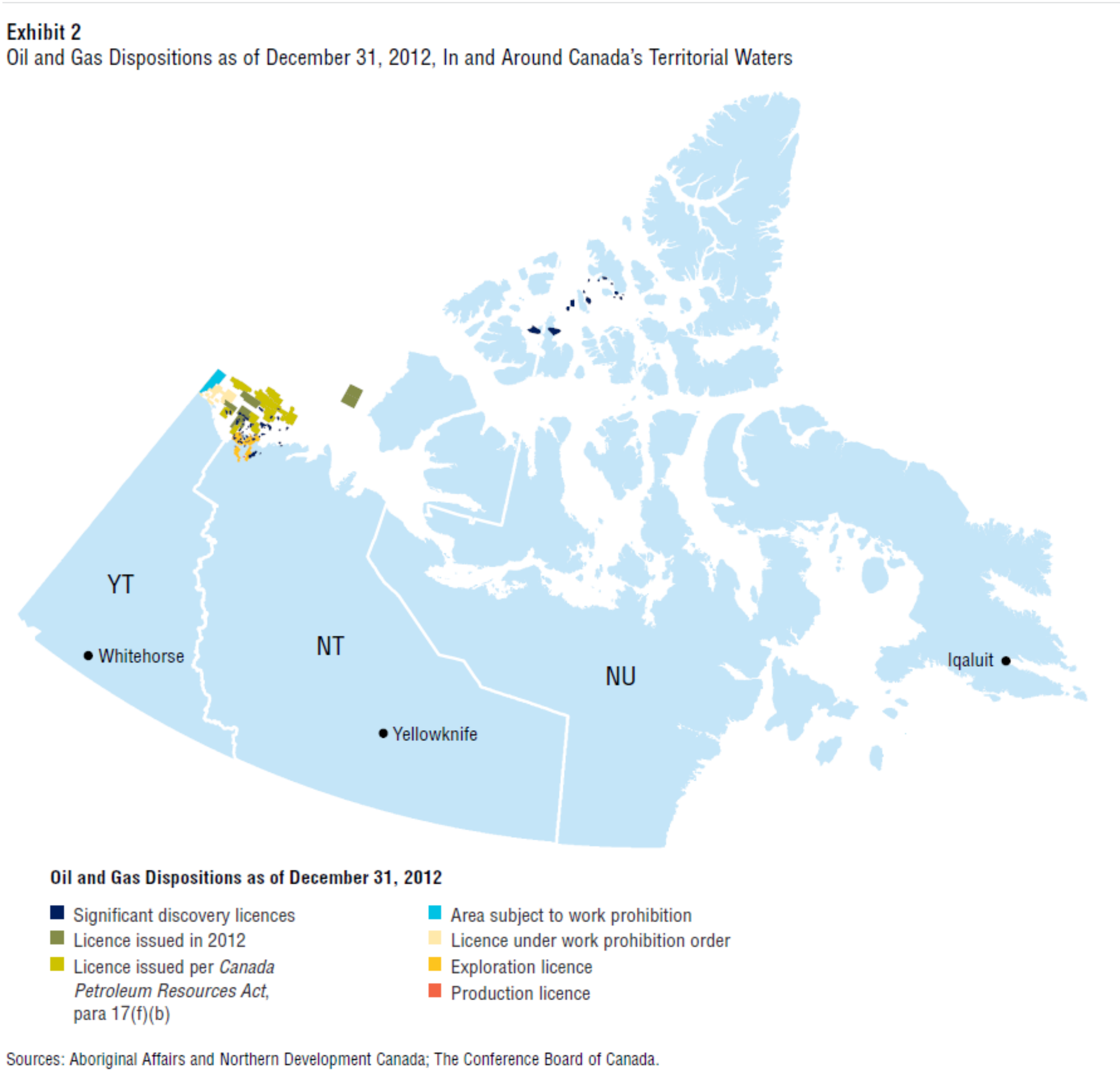


Figure E.2: Oil and gas in Canada's territorial waters.

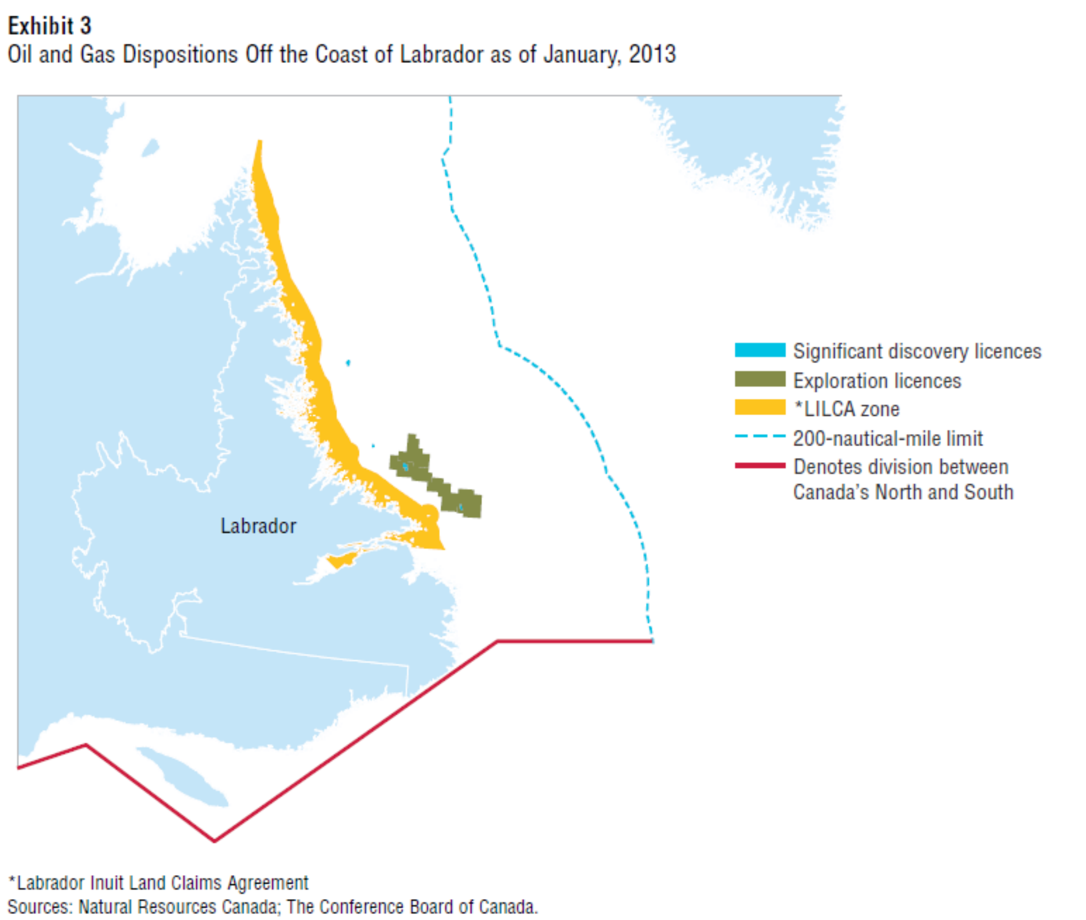


Figure E.3: Oil and gas off coast of Labrador.

E.2 CFN Northern Assets: Transportation Infrastructure in Remote Communities (Bristow, M. and Gill, V., 2011)

A general point is made that transportation infrastructure in Northern communities is significantly more expensive to develop than in the South. At the same time failure of infrastructure in the North can result in bare grocery store shelves or disruption from emergency medical services. Transportation infrastructure in Canada's North is sparse.

The effects of climate change are discussed, which is causing temperatures to rise more quickly in the North than in other regions of Canada. In permafrost zones, foundations are engineered to rest upon frozen ground. Warming temperatures cause areas of discontinuous permafrost to move further north, with regions of thawing permafrost. The result is "ground slumping, tilted trees, sinkholes, and other disturbances", along with declining viability of winter roads.

This can have a significant impact on Northern communities and resource development projects that rely on winter roads. Typically, these roads are used beginning in November or December and are viable until March or April, but milder winters are disrupting this schedule.25 In cases where the only other option is airlift, this results in a significant increase in the cost of supplies. All-weather roads offer an alternative for future construction. Figure E.3 shows the current road infrastructure in Canada.

Investments are often required for projects that are not seen as being economically justified but which are vital for economic and community development. Benefit-cost analyses for these projects must capture a full range of economic and social benefits unique to Northern communities. The report correctly advocates this kind of tool, benefit cost analysis that acknowledges all benefits. Northern communities that rely on a single main industry may be confronted with difficulties if that industry winds down. This is the “boom-and-bust” scenario mentioned in the “Changing Tides” report summarized above.

Marine transport offers the least expensive transportation method for freight and is used for transporting fuel, groceries, and other commercial freight to the Northwest Territories, Nunavut, and the Northern regions of provinces with tidewater access. At the same time, there is very little marine infrastructure in the North, and almost none in Nunavut. Cargo is often offloaded onto beaches, and access to these landing sites can be unpredictable. The marine shipping season is short, ranging from one to five months, depending on the location of the community.

It is noted that Baffinland Iron Mines Corporation is planning to build a 143-km railway, a deep-sea port, and an airstrip to service its Mary River iron ore mining project.

The report considers a case study of Churchill, Manitoba. This port is not connected to the road system in Northern Manitoba, but has access to air, rail, and marine transportation, air and rail being available year-round. Churchill is also the home to Canada’s only operating deepwater port in the Arctic region, making it a possible shipping hub for the Far North. A number of key issues in the Churchill case study provided background for development in other Northern communities. Substantial funding is often required for ongoing operating and maintenance. Full life-cycle costs are important. Public resources are already scarce, and inventive solutions that target the most cost- effective means of achieving economic and social policy objectives are needed.

It is advocated to consider traditional and alternative financial arrangements, including public-private partnerships. Both public and private interests could be served by transportation infrastructure projects in the North.

The design, construction, and operation of new transportation infrastructure must include measures that account for the potential effects of climate change. It is stated that Manitoba has taken these issues into account in the planned design of the proposed Manitoba–Nunavut Highway.

Conflicting objectives among stakeholders was a theme that emerged frequently in the interviews conducted for the report.

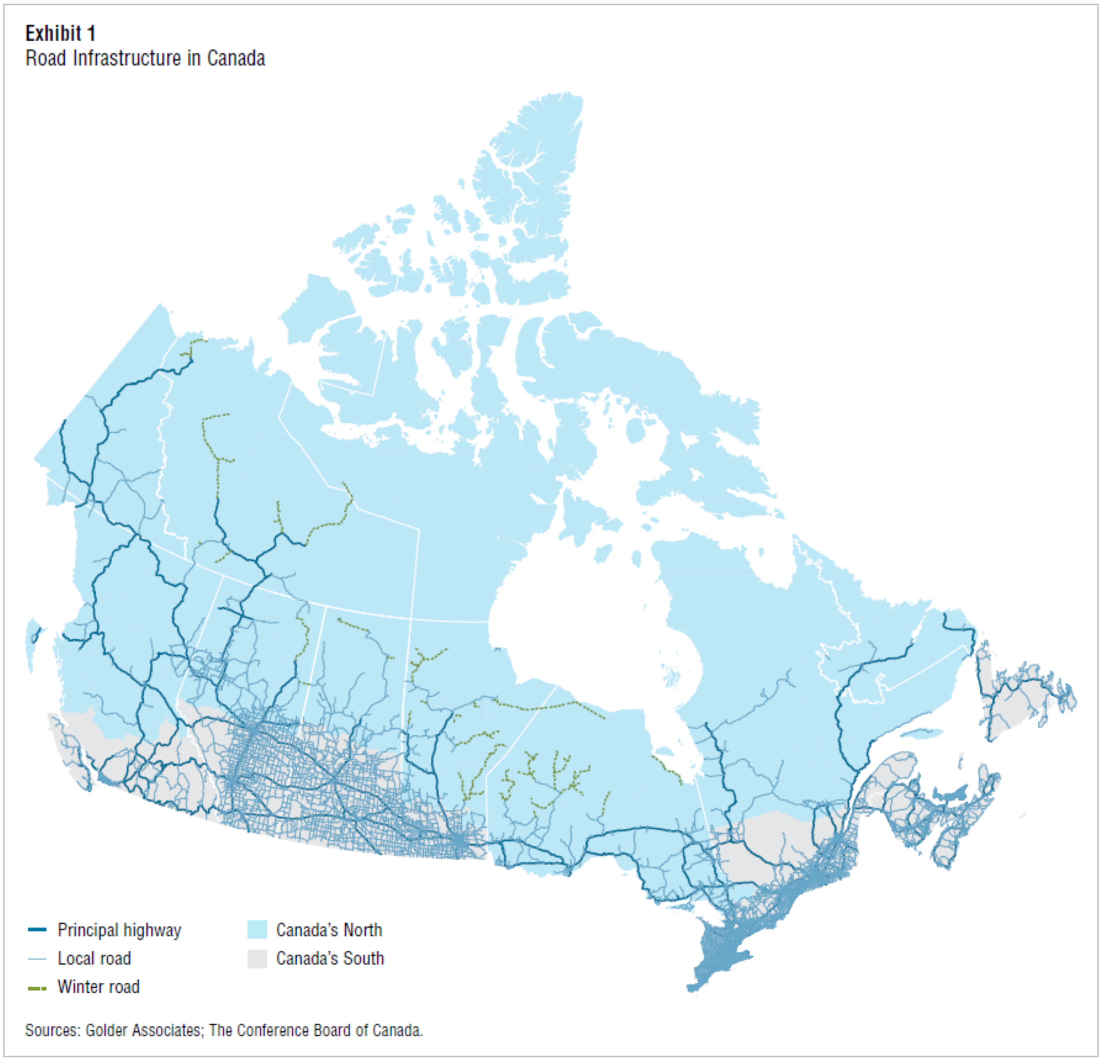


Figure E.4: Road infrastructure in Canada

E.3 CFN Future of Mining

This report provides an excellent overview of the potential for mining in the North and measures to help realize this potential. Mining already provides a significant economic driver for development and creating opportunities for the North of Canada. This report defines policy initiatives which can be the basis for helping realize this potential. The report covers five primary areas:

- Canada's northern mining potential to the year 2020
- business factors related to mining development
- impacts and benefits of mining for northern communities
- addressing environmental stewardship and the impacts of mining
- creating a sustainable future: what happens after a mine closes?

and concludes with six key recommendations.

Mining is seen as a future economic driver of Canada's North. The long-term global demand for commodities is increasing, even if there are short-term swings, and Canada is well positioned to take advantage of this opportunity. The overall Northern metallic mineral output is about $4b annually, with about $1b from the Yukon, Northwest Territories and Nunavut. This is expected to almost double by 2020. There is also about $1/2b spent annually in the three northern territories for mineral exploration. World markets are not controlled by Canada, but there are factors which are within Canada's control. This potential can be realized only if key regulatory, infrastructure, and human resource challenges are met. All factors necessary for mining development must be looked at in a holistic fashion. Governments, industry, and Aboriginal groups need to coordinate their efforts, and must have better knowledge of their roles and responsibilities to be effective and to avoid duplication of processes.

Regulatory processes are currently complex and cumbersome, and lack clarity and consistency for all proponents. For example, many project review boards do not have the capacity to ensure project reviews are completed in a timely manner. This presents significant obstacles for investors. This report recognizes that the federal government has taken important steps toward the "one project, one assessment" goal, and that this could lead to greater cooperation and coordination between the federal and provincial/territorial governments. However, Aboriginal governments need to be full and equal participants in decision-making. Challenges still remain with respect to the realization of land claims and self-government agreements and their role in resource management and development.

The infrastructure gaps are often the greatest deterrents to mining development in Canada's remote Northern regions. Many companies must build their own transportation, communication, and/or energy infrastructure, adding significant costs to projects. To ease this financial burden on industry, governments need to invest broadly in Northern infrastructure and make use of public-private partnerships to share risks, costs, and benefits.

The mining industry worldwide is facing an impending labour shortage, and Canada is not immune to this. Younger Canadians from all backgrounds are ignoring mining as a career option. Therefore, mining companies must work to recruit and retain new workers and look to under- represented groups—such as women, new

Canadians, and Aboriginal Peoples—as potential sources of labour. Additionally, education and targeted training programs are needed to ensure that local populations are able to benefit fully from employment opportunities.

Companies and governments need to begin consultation processes as early as possible in order to provide communities with the tools necessary to make informed decisions. While this is strongly recommended, companies are not obligated to do it. However, mechanisms like impact and benefit agreements (IBAs) can be instrumental in ensuring that a community's needs are met and properly accommodated. Furthermore, ongoing consultation throughout all phases of mining activity—from exploration to mine closure—helps build and foster positive relationships.

Improved regulations, industry-led initiatives, technological innovations and traditional ecological knowledge have all contributed to improving the industry's environmental performance. Companies have also worked to minimize their impacts on the land, and mine closure and remediation have come a long way since mining's early days. Despite all of this, many important environmental concerns remain, particularly around the uncertainties of the long-term impacts of mining on flora and fauna.

Mining projects can deliver immediate benefits to residents in the form of jobs, higher incomes, business opportunities, and infrastructure. However, communities can be unprepared for mine closure. Robust closure plans should be in place to help diversify the local economy, especially when the community is reliant on a single resource. Mining companies, governments, and local communities should work together at the outset of a project to provide solutions that will mitigate the impacts of closure.

Each issue presents its own unique challenges and requires solutions and recommended actions in its own right. Looking at these issues together, the findings of this report suggest the following priority areas for policy development to support the future of sustainable mining in Canada's North:

- a competitive business environment for the mining industry,
- addressing infrastructure gaps and needs,
- recruitment initiatives aimed at women, new Canadians, youth, and Aboriginal workers,
- meaningful community consultations and ensuring the implementation of Aboriginal land claims and resource development agreements,
- improving regulatory processes and personnel turnover in government regulatory bodies, and
- further investments in geoscience.

E.4 CCA Northern Ocean Science in Canada: Meeting the Challenge, Seizing the Opportunity

Recognizing the importance of ocean science, the Canadian Consortium of Ocean Research Universities (CCORU) asked the Council of Canadian Academies (CCA) to undertake an assessment of the state of ocean science in Canada. The report was carried out by an expert panel formed by the Council of Canadian Academies (Council of Canadian Academies, 2013).

Canada's existing research capacity was investigated. The state of Canada's ageing research fleet was noted. Canada's output of ocean science was considered to be in the top rank at present, but at risk. Funding opportunities, for instance those offered by the Canada Foundation for Innovation, are enabling the establishment and management of large-scale infrastructure. This includes vessels and observation networks. Consortia such as CCORU, are emerging. These networks and alignments have resulted in several innovative, world-leading initiatives. Despite these advances, the Panel identified the gaps in the coordination and alignment of the ocean science community in Canada. The principal relate to lack of a national vision for ocean science, and of effective national-level mechanisms to coordinate resources and sharing of infrastructure and knowledge among ocean scientists. Finally, an information gap is perceived: a mechanism or repository that systematically collects and regularly updates information on key research activities in ocean science for the entire country is needed.

E.5 True North: Adapting Infrastructure to Climate Change in Northern Canada

This report was carried out by the National Round Table on the Environment and the Economy (2009).

By means of research and extensive consultation of stakeholders, the risks to northern infrastructure posed by climate change was investigated together with opportunities for adaptation. The recommendations were primarily addressed to government and were focussed on adaptation to climate change and the use of current and future policy and decision-making processes to this end. Building northern capacity to adapt to climate change was a prime motivation.

E.6 Arctic Marine Shipping Assessment (AMSA) 2009 (Arctic Council)

The Arctic Council in 2004 commissioned a working group to prepare the subject report. The report deals with climate change, Arctic marine transport, governance of Arctic shipping, current marine use, future scenarios, human and environmental considerations, as well as infrastructure. Natural resource development (hydrocarbons, hard minerals and fisheries) and regional trade were seen as the key drivers of future Arctic marine activity. A lack of major ports, except for those in northern Norway and northwest Russia, and other critical infrastructure poses significant difficulties for future Arctic marine operations. Destinational shipping is emphasized. Many Arctic residents depend on marine resources for subsistence and it is suggested that constructive and early engagement of local residents in planned Arctic marine development projects will be beneficial to their well-being.

The report is commendable in terms of the range and thoroughness of its coverage. Recommendations were made on arctic marine safety, protection of arctic people and the environment, and building arctic marine infrastructure. Of particular interest are that the Arctic states should support the development and implemention of a comprehensive, multi-national Arctic Search and Rescue (SAR) instrument, and that the Arctic states should cooperate in the development of Arctic marine infrastructure.

E.7 From Impacts to Adaptation; Canada in a Changing Climate 2007

This report was sponsored by Natural Resources Canada and Environment Canada (Lemmen et al., 2008). Its focus is on changing climate, and adaptation to this change. The report points out that adaptive capacity in Canada is high, but that resource-dependent and Aboriginal communities are particularly vulnerable to climate changes. This vulnerability is magnified in the Arctic.

E.8 The Past is Always Present: Review of Offshore Drilling in the Canadian Arctic (National Energy Board, 2011)

Same-season relief well issue is covered. Regarding this matter, NEB affirmed its intent to retain its same-season relief well policy. But the report also included the statement that “an applicant wishing to depart from our policy would have to demonstrate how they would meet or exceed the intended outcome of our policy. It would be up to us to determine, on a case-by-case basis, which tools are appropriate.... We acknowledge that there is a continual evolution of technology worldwide, including the technology needed to kill an out-of-control well. We are open to changing and evolving technology.”

E.9 CARD Arctic Development Roadmap (CARD, 2012)

This report is focused on the Oil and Gas industries. As part of its planning process, the Centre for Arctic Resource Development (CARD) developed the “Arctic Development Roadmap” (CARD, 2012). The importance of this document for the present CAE study is that, in order to develop the roadmap, a series of interviews were conducted with the major oil and gas operators and consultants in order to get their perspectives. The oil and gas operators who were interviewed included ExxonMobil, Suncor, Husky Energy, Statoil, Chevron, Imperial Oil, Shell and ConocoPhillips. Appendix QQ lists past planning studies of relevance to the Canadian Arctic.

Appendix F: Previous Planning studies (Oil and Gas)

Table F.1 lists some earlier R&D planning studies for Canada's Arctic oil and gas. The Table is reproduced from CARD (2012) and is contained in their "Roadmap" which is discussed in the report.

Table F.1: Past studies on Arctic oil and gas development

Table 2-1. Summary of documents reviewed for this project

Report Title	Year	Author(s) or Company
A Research Planning Study for Canada's Frontier Oil and Gas	1992	Croasdale, K.R., and McDougall, J.
Review and Assessment of PERD and Other Ice-Structure Interaction Work	1992	Wright, B., and Masterson, D.
Current and Future Hydrocarbons Research & Development	1999	Croasdale, K.R., et al.
Study of Iceberg Scour & Risk in the Grand Banks Region	2000	Croasdale and Associates, et al.
Focused Research Opportunities - Atlantic Canada Petroleum Related Research and Development Public Stakeholders Forum	2004	Ewida, Ahmed (Petro Canada)
Report of the Research & Development Sub-Committee to the Industrial Opportunity Working Group of the Atlantic Energy Roundtable	2005	Canadian Energy Board
Ice-Related R&D Requirements for Beaufort Sea Production Systems	2005	Wright, B. & Associates Ltd.
Scoping Study: Ice Information Requirements for Marine Transportation of Natural Gas from the High Arctic	2005	Timco, G.W., Gorman, B., Falkingham, J., and O'Connel, B.
Report to the Industrial Opportunities Working Group of the Atlantic Energy Roundtable	2005	Research & Development Sub-Committee
Norway's Technology Strategy for Value Creation on the NCS and Enhanced Competitiveness in the Oil and Gas Industry	2006	OG21 - established by the Ministry of Petroleum and Energy (MPE)
Technology Strategy for the Arctic – Extract from the OG21 Strategy	2006	Norwegian Ministry of Petroleum & Energy
Achievements and Future Research Needs in Ice Engineering	2006	Schwarz, J.

Survey of Canadian Arctic Captains: current status and research needs	2007	Timco, G.W. and Gorman, R.
Arctic Offshore Technology Assessment of Exploration and Production Options for Cold Regions of the US Outer Continental Shelf	2008	IMV Projects Atlantic
Transportability of Fabricated Modules through the Northwest Passage	2008	Kendrick, A
Arctic Relief Well Drilling: An Oil and Gas Company Perspective	2009	Chevron
Arctic Marine Shipping Assessment	2009	Arctic Council, Norway
Technology Requirements for Arctic Offshore Developments	2010	Noble, Peter (ConocoPhillips)
Research Needs in the Beaufort Sea: Unique Challenges of Exploring in Deepwater Regions	2010	Hawkins, James (Imperial Oil)
Barents 2020: Assessment of International Standards for Safe Exploration, Production and Transportation of Oil and Gas in the Barents Sea	2010	DNV
Arctic Standards – A Comparison and Gap Study	2011	Ghoneim, G. A.

Appendix G: Natural Resources

G.1 Sources

The Future of Mining in Canada's North, by Gilles Rhéaume and Margaret Caron-Vuotari, The Conference Board of Canada, Report January 2013.

G.2 Preface

Mining and its supporting industries will continue to be important economic drivers in many of Canada's Northern regions over the course of the next decade. While great potential for mining development exists, this potential must be approached in a balanced way. This report discusses a number of important factors— and their interrelationship with one another—that must be considered to ensure that both the positive and negative impacts of mining projects are fully understood. The findings from this report provide policy-makers, industry leaders, and communities with insight on steps that can be taken to support the future of sustainable mining in Canada's North.

> *Nunavut Mineral Exploration, Mining and Geoscience Overview 2012*, Minerals Division at Aboriginal Affairs and Northern Development Canada's Nunavut Regional Office.

http://www.nrcan.gc.ca/earth-sciences/resources/federal-programs/geomapping-energy-minerals/10904

G.3 GEM: Geo-Mapping for Energy and Minerals

Researchers with Natural Resources Canada's (NRCan's) Geo-mapping for Energy and Minerals (GEM) Program are providing their geo-scientific expertise to help realize this potential. The goal is to improve regional geological mapping in the north for responsible resource exploration and development.

"This information is helping northerners to make informed choices on land use that balance conservation with development of northern resources," says Donna Kirkwood, Director General, Central and Northern Canada Branch, Geological Survey of Canada, NRCan.

G.4 GEM the Next Phase

The second phase of the GEM program will be used to further develop geological maps, data sets and knowledge. The new knowledge and data will complete regional-scale coverage of Canada's North by 2020, focusing on areas of high resource potential.

As new geo-maps are produced, they are made publicly accessible on-line and free of charge to industry investors, land-use planners, and community agencies.

"We are also working with provincial and territorial governments and Aboriginal organizations, as well as seeking advice from northerners in implementing this program in order to maximize the benefits for northerners," adds Donna Kirkwood.

Table G.1: Oil and Gas Resources

Region	Crude Oil 10^6 m^3	(Million Barrels)	Natural Gas 10^9 m^3	(TCF)
Northwest Territories and Arctic Offshore	187.9	1182.5	457.6	16.2
Nunavut and Arctic	51.3	322.9	449.7	16
Arctic Offshore Yukon	62.5	393.8	4.5	0.2
Total	301.7	1899.1	911.8	32.4

Table G.2: Northwest Territories

Mine	**Owner**	**Commodity**	**Basic facts**	**Latest developments**
Ekati Mine	BHP Billiton, Chuck Fipke and Stu Blusson	Diamonds	Canada's first and largest diamond mine, 310 km. NE of Yellowknife. Open pit and underground. Mine life to 2019. Workforce approximately 1,500	2011 Year in Review report released. BHP Billiton is conducting review of diamonds business and potential sale.
Diavik Mine	Rio Tinto and Harry Winston	Diamonds	Canada's largest diamond producer, 300 km NE of Yellowknife. Open pit and underground, but will be all underground in 2012. Mine life to 2023. Workforce approximately 1,000.	One million tonne underground production reached in May. Mine life now confirmed to 2023 with production from additional pipe, called A21. Rio Tinto is conducting review of diamonds business and potential sale.
Snap Lake Mine	De Beers	Diamonds	Canada's first all underground diamond mine. Located 220 kilometres NE of Yellowknife. Mine life to 2028. Workforce approximately 678.	Commenced commercial production on January 16, 2008 and the official mine opening took place on July 25, 2008.

Mine	Owner	Commodity	Basic facts	Latest developments
Cantung Mine	North American Tungsten	Tungsten, copper	Cantung is in the mountains of western Northwest Territories, approx. 300 km by road NE of Watson Lake, Yukon. Mine life to 2014. Approximately 200 jobs.	June news release reports significant new underground exploration results in "Amber Zone."
Nechalacho	Avalon Rare Metals	Rare earth metals	Proposed underground mine 100km SE of Yellowknife. Estimated mine jobs: 200 Nechalacho project at Thor Lake, located 100 km southest of Yellowknife.	Avalon submitted responses to 2nd round of information requests to the environmental impact review board for environmental assessment. Avalon signed 1st of 3 agreements with equity participation with the Deninu K'ue First Nation
NICO	Fortune Minerals Ltd.	Cobalt-gold bismuth copper	Proposed open pit and underground mine located 50 km NE of Whati. Estimated mine jobs: 150	Environmental public hearings have concluded.
Yellowknife Gold Project	Tyhee Gold Corp	Gold	Proposed open pit and underground mine of 4 deposits about 90 km NE of Yellowknife. Estimated mine jobs: 238	Positive feasibility study announced Aug. 15, submitted to Review Board as part of active environmental review.
Prairie Creek	Canadian Zinc Corporatoin	Lead-zinc silver	Proposed underground mine 120 km west of Fort Simpson. Estimated mine jobs: 220	Project in permitting and licensing. Preliminary Feasibility Study results issued June 27.
Gahcho Kue	De Beers & Mountain Province	Diamonds	Proposed open-pit diamond mine approximately 180 km ENE of Yellowknife, NT. Estimated mine jobs: 360	Public hearing dates for Environmental Impact Review finalized for Nov. 30-Dec. 8 in Dettah, Lutsel K'e, & Yellowknife.
Pine Point	Tamerlane Ventures	Lead-zinc	Company proposes underground mine east of Hay River using freeze technology for water management. Estimated mine jobs: 225	Company has requested change to audit and decline from shaft to test mine the R-190 deposit. Resource is defined; permitted for construction; extensive infrastructure
Courageous Lake	Seabridge Gold	Gold	Proposed open pit mine 240 km northeast of Yellowknife	Positive Preliminary Feasibility Study released July 24 with 6.5 million ounces proven and probable reserves. Exploration budget of $8.5 million this year. Annual report released in May.

Mine	Owner	Commodity	Basic facts	Latest developments
Selwyn Project	Selwyn Chihong	Zinc, lead	Proposed underground mine in Yukon on NWT border and access is through NWT. Agreements signed with NWT (Sahtu) Aboriginal land corporations	Feasibility study to be done this year. Resource updated in August and surpasses 180 million tonnes. In early Sept, Selwyn suspended its Strategic Review Process as it contemplated the effects of "the worst economic times in recent memory" and potential sale of the project.

Table G.3: Nunavut

Mine	Owner	Commodity	Basic facts	Latest developments
Meadowbank Gold Mine	Agnico-Eagle Mines	Gold	Open-pit mine located in the Kivalliq Region, 300 km west of Hudson Bay and 70 km N of Baker Lake. Mine jobs: 450	NTI received first royalty payment in 2012. July second quarter reports record quarterly gold production of 98,403 ounces
Mary River	Baffinland Iron Mines	Iron	Proposed open pit mine with railway and port 936 km N of Iqaluit with 5 known deposits. Estimated construction jobs: 3,500 Estimated mine jobs: 715	Final hearings for environmental assessment completed in July 2012. NIRB has granted approval of the project with 184 conditions to be met.
Kiggavik	AREVA Resources	Uranium	Proposed uranium mine 80 km W of Baker Lake. Estimated Construction jobs: 750 Estimated mine jobs: 1,300	Areva anticipates submitting responses to its Draft Environmental Impact Statement, to the impact review board by Jan. 31, 2013.
Jericho Diamond Mine	Shear Diamonds Ltd.	Diamonds	Project to reassess viability of reopening the former diamond mine, 255 km SSE of Kugluktuk. Estimated mine jobs: 150-200	Shear suspends stockpile production due to low diamond prices, Sept. 4, 2012
Meliadine Gold	Agnico-Eagle Mines	Gold	Possible gold mine, 5 deposits, the largest of which is the Tiriganiaq deposit, 25 km NE of Rankin Inlet. Estimated construction jobs: 600 Estimated mine jobs: 350 – 400	Plan to complete feasibility study in 2013; NIRB approved environmental assessment exemption of “Phase 1 – all-weather Road” on May 23, 2012. Road located on Inuit Owned Land.

Mine	Owner	Commodity	Basic facts	Latest developments
Hackett River	Xstrata Zinc Canada	Zinc, silver, copper, lead and gold	One of largest undeveloped VMS massive sulphide deposits in the world, hosting significant silver deposits. 104 km SSW of Bathurst Inlet. Estimated mine jobs: 300	Camp opened Feb. 20, 2012, Pre-feasibility study team being assembled.
Back River	Sabina Gold & Silver Corp.	Gold	Approximately 60 km from Hackett River. Potential to mine multiple deposits by open pit and underground. Workforce up to 900.	Exploration budget for 2012 hit $60M. Project description submitted to NIRB in July to trigger EA.
Izok Corridor Project (with High Lake)	MMG Resources Inc.	Copper, Zinc, Gold, Silver	Izok and High Lake ESE of Kugluktuk. Plans call for single processing facility at Izok, 350 km all-season road to port at Gray's Bay. Shipping to Europe and Asia. Total jobs 710 with 400 on site.	On Sept. 4, MMG submitted project proposal to NIRB to trigger official environmental assessment process.
Ulu & Lupin	Elgin Mining Inc.	Gold	Located SE of Kugluktuk. Lupin mine: past production of 3.7 million ounces. Ulu deposit: indicated mineral resource: 751,000 tonnes at 11.37 grams of gold per tonne.	Elgin purchased both properties from MMG Resources in July, 2011. Winterization of work camp at Lupin Drilling at Ulu began April 2012.
Roche Bay	Advanced Exploration	Iron	Over 500 million tonnes of indicated resources within 6 km of a natural deep-water harbour at Roche Bay. Estimated construction jobs: 450 Estimated mine jobs: 370 – 380	Positive feasibility study announced Aug. 10, 2012, confirms net present value of $642 million (pre-tax)
Chidliak	Peregrine Diamonds Ltd.	Diamonds	Located 180 km S of Pangnirtung. Contains 59 known diamond-hosting formations.	Peregrine announced potential joint venture agreement with De Beers, Sept. 5, 2012.
Doris North/ Hope Bay	Newmont Mining Corp	Gold	Proposed gold mines 130 km S of Cambridge Bay covers the majority of the Hope Bay Greenstone Belt. Estimated mine jobs: 300	Work postponed indefinitely while project under review

Appendix H: List of wells drilled in Canadian Beaufort Sea

Table H.1: Exploration wells drilled in the Canadian Beaufort Sea by date and platform type (from Callow, 2012)

Table 1. Drilling Activity in the Beaufort Sea

WELL NAME	WELL OPERATOR	WELL SPUD DATE	RIG RELEASE	DRILLING PLATFORM	WATER DEPTH (M)
NUKTAK C-22	Imperial	16-Dec-1972	8-Mar-1973	Land on Hooper Is	NA
IMMERK B-48	Imperial	17-Sep-1973	22-Dec-1973	Sacrificial Beach Is	3
ADGO F-28	Imperial	28-Dec-1973	19-Mar-1974	Sandbag Retained Is	2
PULLEN E-17	Imperial	21-Apr-1974	11-Jul-1974	Sandbag Retained Is	2
UNARK L-24	Sun	26-Sep-1974	24-May1975	Hauled Island	2
PELLY B-35	Sun	5-Oct-1974	14-Feb-1975	Hauled Island	2
ADGO P-25	Imperial	2-Jan-1975	28-Mar-1975	Sandbag Retained Is	2
NETSERK B-44	Imperial	6-Jan-1975	8-Jun-1975	Sandbag Retained Is	5
ADGO C-15	Imperial	21-Apr-1975	25-Jul-1975	Sandbag Retained Is	2
IKATTOK J-17	Imperial	10-Jul-1975	28-Feb-1976	Sandbag Retained Is	2
NETSERK F-40	Imperial	8-Nov-1975	9-May-1976	Sandbag Retained Is	8
SARPIK B-35	Imperial	2-Apr-1976	4-Sep-1976	Sandbag Retained Is	4
KOPANOAR D-14	Dome	8-Aug-1976	26-Sep-1976	Canmar Explorer 3	60
TINGMIARK K-91	Dome	11-Aug-1976	18-Oct-1977	Canmar Explorer 1/3	28
NEKTORALIK K-59	Dome	23-Sep-1976	17-Oct-1977	Canmar Explorer 2/3	64
KOPANOAR M-13	Dome	27-Sep-1976	10-Sep-1979	Canmar Explorer 3	57
KUGMALLIT H-59	Imperial	30-Sep-1976	10-Nov-1976	Sandbag Retained Is	5
ARNAK L-30	Imperial	5-Oct-1976	16-Mar-1977	Sacrificial Beach Is	9
UNARK 2L-24	Sun	19-Oct-1976	8-May-1977	Hauled Island	2
KANNERK G-42	Imperial	30-Mar-1977	14-May1977	Sacrificial Beach Is	8
UKALERK C-50	Dome	18-Jul-1977	3-Oct-1977	Canmar Explorer 1	42
KAGLULIK A-75	Dome	19-Jul-1977	6-Aug-1978	Canmar Explorer 3	39
NERLERK M-98	Dome	4-Oct-1977	28-Aug-1982	Canmar Explorer 1/3	52
ISSERK E-27	Imperial	4-Dec-1977	5-May-1978	Sacrificial Beach Is	13
NATSEK E-56	Dome	10-Jul-1978	8-Oct-1979	Canmar Explorer 2-4	34
UKALERK 2C-50	Dome	10-Aug-1978	11-Oct-1979	Canmar Explorer 1	42
TARSIUT A-25	Dome	18-Oct-1978	28-Jul-1980	Canmar Explorer 3	20
KAGLULIK M-64	Dome	3-Nov-1978	10-Jul-1979	Canmar Explorer 2	27
ADGO J-27	Esso	5-Apr-1979	7-Aug-1979	Sandbag Retained Is	2
KENALOOAK J-94	Dome	20-Sep-1979	1-Nov-1982	Canmar Explorer 2-4	68
KOPANOAR L-34	Dome	11-Oct-1979	26-Nov-1979	Canmar Explorer 2	58
KOAKOAK O-22	Dome	5-Nov-1979	31-Oct-1981	Canmar Explorer 1/2	49
KOPANOAR 2L-34	Dome	26-Nov-1979	28-Nov-1979	Canmar Explorer 4	56
ISSUNGNAK O-61	Imperial	6-Feb-1980	8-Jul-1980	Sacrificial Beach Is	37
KILANNAK A-77	Dome	23-Jun-1980	4-Sep-1981	Canmar Explorer 3	38
ORVILRUK O-03	Dome	9-Jul-1980	16-Sep-1980	Canmar Explorer 1	60
KOPANOAR I-44	Dome	10-Jul-1980	1-Aug-1980	Canmar Explorer 4	59
KOPANOAR 2I-44	Dome	2-Aug-1980	28-Oct-1981	Canmar Explorer 2	58
ISSUNGNAK 2O-61	Imperial	2-Oct-1980	13-Aug-1981	Sacrificial Beach Is	19
N. ISSUNGNAK L-86	Gulf	17-Jul-1981	17-Oct-1981	Canmar Explorer 2	26
ALERK P-23	Imperial	21-Sep-1981	24-Dec-1981	Sacrificial Beach Is	12
IRKALUK B-35	Dome	27-Sep-1981	4-Oct-1982	Canmar Explorer 4/2	58
E. TARSIUT N-44	Gulf	10-Dec-1981	7-Jun-1982	Concrete Caisson	19
W. ATKINSON L-17	Imperial	1-May-1982	25-Jun-1982	Sandbag Retained Is	7
E. TARSIUT N-44A	Gulf	8-Jun-1982	19-Sep-1982	Concrete Caisson	19
KIGGAVIK A-43	Gulf	21-Jul-1982	17-Oct-1982	Canmar Explorer 1	18

Table 1. Drilling Activity in the Beaufort Sea (cont.)

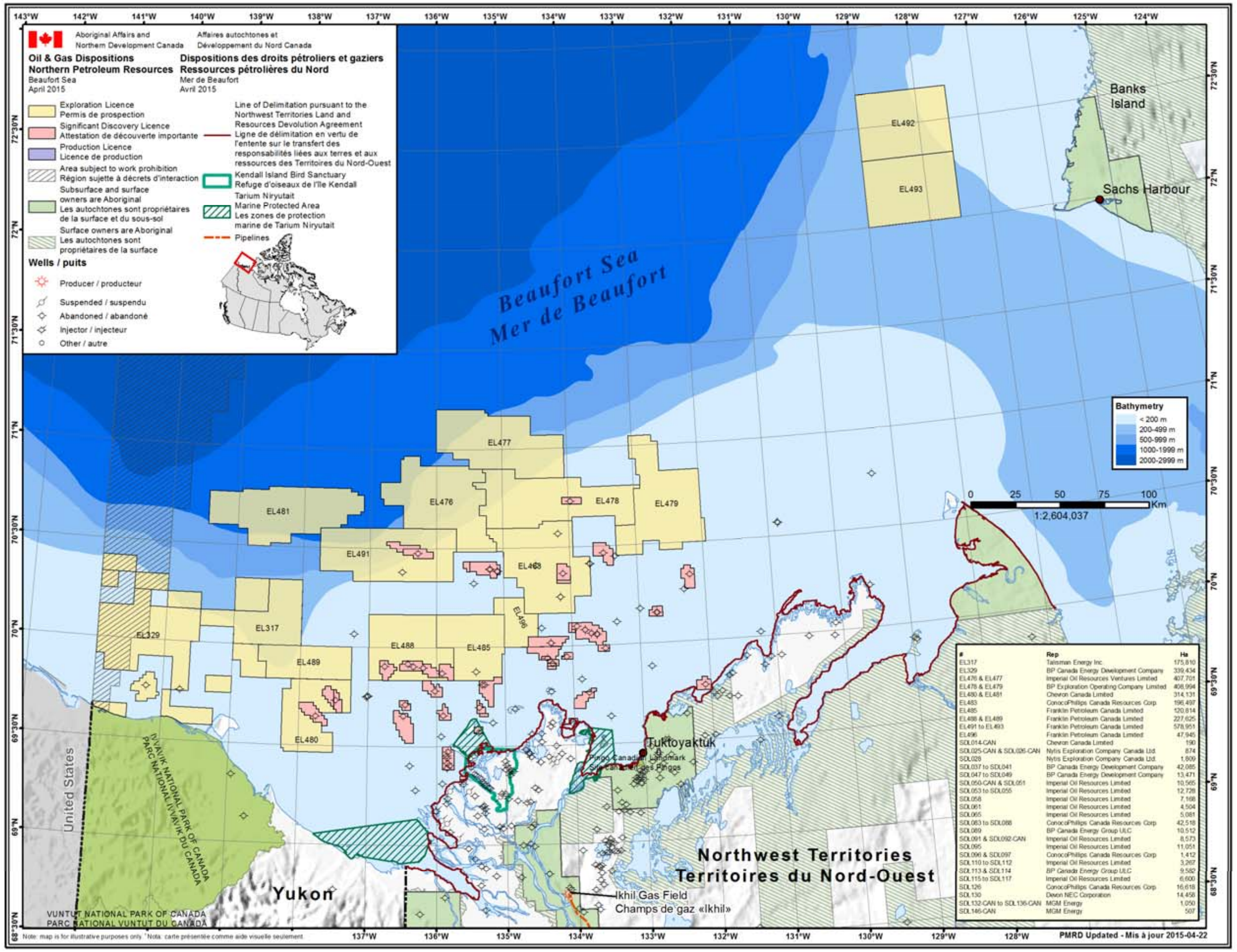
WELL NAME	WELL OPERATOR	WELL SPUD DATE	RIG RELEASE	DRILLING PLATFORM	WATER DEPTH (M)
AIVERK I-45	Dome	5-Oct-1982	23-Oct-1982	Canmar Explorer 2	62
AIVERK 2I-45	Dome	3-Nov-1982	11-Oct-1984	Canmar Explorer 4/1	61
ITIYOK I-27	Imperial	5-Nov-1982	2-May-1983	Sacrificial Beach Is	14
UVILUK P-66	Dome	10-Nov-1982	21-May1983	SSDC	30
NATIAK O-44	Dome	16-Jul-1983	25-Sep-1984	Canmar Explorer 2	44
HAVIK B-41	Dome	17-Jul-1983	24-Aug-1986	Canmar Explorer 1	35
SIULIK I-05	Dome	25-Jul-1983	18-Oct-1984	Canmar Explorer 4	52
ARLUK E-90	Dome	30-Jul-1983	13-Oct-1985	Canmar Explorer 3	57
PITSIULAK A-05	Gulf	22-Aug-1983	26-Jul-1984	Kulluk	27
KADLUK O-07	Imperial	25-Sep-1983	24-Apr-1984	CRI	14
AMAULIGAK I-44	Gulf	7-Oct-1983	15-Nov-1983	Kulluk	20
KOGYUK N-67	Gulf	28-Oct-1983	30-Jan-1984	SSDC	28
AMAULIGAK J-44	Gulf	16-Nov-1983	23-Sep-1984	Kulluk	31
AMERK O-09	Imperial	22-Aug-1984	3-Mar-1985	CRI	26
W. TARSIUT P-45	Gulf	25-Sep-1984	24-Dec-1984	Molikpaq	22
NERLERK J-67	Dome	26-Sep-1984	24-Oct-1985	Kulluk	45
ADGO H-29	Imperial	27-Sep-1984	12-Jan-1985	Sandbag Retained Is	3
NIPTERK L-19	Imperial	3-Oct-1984	23-Mar-1985	Sacrificial Beach Is	11
AKPAK P-35	Gulf	17-Oct-1984	8-Nov-1985	Kulluk	41
NIPTERK L-19A	Imperial	21-Apr-1985	15-Jul-1985	Sacrificial Beach Is	11
AKPAK 2P-35	Gulf	8-Jul-1985	14-Aug-1985	Kulluk	41
ADLARTOK P-09	Dome	8-Aug-1985	17-Oct-1985	Canmar Explorer 3	68
EDLOK M-56	Dome	10-Aug-1985	18-Sep-1985	Canmar Explorer 4	32
AMAULIGAK I-65	Gulf	24-Sep-1985	21-Jan-1986	Molikpaq	23
ADGO G-24	Imperial	7-Oct-1985	7-Jan-1986	Sandbag Retained Is	2
AAGNERK E-56	Gulf	28-Oct-1985	26-Jun-1986	Kulluk	20
MINUK I-53	Imperial	27-Nov-1985	2-May-1986	Sacrificial Beach Is	15
NORTH ELLICE L-39	Chevron	25-Jan-1986	20-Apr-1986	Sandbag Retained Is	2
AMAULIGAK I-65A	Gulf	28-Jan-1986	20-Mar-1986	Molikpaq	23
AMAULIGAK I-65B	Gulf	20-Mar-1986	19-Sep-1986	Molikpaq	23
ARNAK K-06	Imperial	27-Apr-1986	12-Aug-1986	Sacrificial Beach Is	8
KAUBVIK I-43	Imperial	22-Oct-1986	10-Jan-1987	CRI	18
ANGASAK L-03	Trillium	24-Feb-1987	12-Apr-1987	Spray Ice Island	5
AMAULIGAK F-24	Gulf	1-Oct-1987	12-Aug-1988	Molikpaq	32
AMAULIGAK 2F-24	Gulf	22-Dec-1987	29-Jan-1988	Molikpaq	32
AMAULIGAK 2F-24A	Gulf	30-Jan-1988	17-Feb-1988	Molikpaq	32
AMAULIGAK 2F-24B	Gulf	15-Apr-1988	7-Aug-1988	Molikpaq	32
AMAULIGAK O-86	Gulf	30-Jun-1988	26-Aug-1988	Kulluk	20
AMAULIGAK CH NO.1	Gulf	12-Aug-1988	7-Sep-1988	Molikpaq	32
AMAULIGAK 2F-24BST	Gulf	27-Jun-1988	7-Aug-1988	Molikpaq	32
NIPTERK P-32	Esso	21-Feb-1989	20-Apr-1989	Spray Ice Island	7
IMMIUGAK N-05	Gulf	1-Jun-1989	10-Jun-1989	Kulluk	32
IMMIUGAK A-06	Gulf	16-Jun-1989	22-Sep-1989	Kulluk	53
KINGARK J-54	Amoco	18-Jul-1989	10-Oct-1989	Canmar Explorer 1	59
ISSERK I-15	Imperial	11-Nov-1989	8-Jan-1990	Molikpaq	12
PAKTOA C-60	Devon	5-Dec-2005	19-Mar-2006	SDC	13

Appendix I: Minerals and Oil and Gas Map

Affaires autochtones et
Développement du Nord Canada

Aboriginal Affairs and
Northern Development Canada

Canada



#	Rep	Ha
EL317	Talisman Energy Inc.	175,810
EL329	BP Canada Energy Development Company	339,434
EL476 & EL477	Imperial Oil Resources Ventures Limited	407,701
EL478 & EL479	BP Exploration Operating Company Limited	408,994
EL480 & EL481	Chevron Canada Limited	314,131
EL483	ConocoPhillips Canada Resources Corp	196,497
EL485	Franklin Petroleum Canada Limited	120,814
EL488 & EL489	Franklin Petroleum Canada Limited	227,625
EL491 to EL493	Franklin Petroleum Canada Limited	578,951
EL496	Franklin Petroleum Canada Limited	47,945
SDL014-CAN	Chevron Canada Limited	190
SDL025-CAN & SDL026-CAN	Nytis Exploration Company Canada Ltd.	874
SDL028	Nytis Exploration Company Canada Ltd.	1,809
SDL037 to SDL041	BP Canada Energy Development Company	42,085
SDL047 to SDL049	BP Canada Energy Development Company	13,471
SDL050-CAN & SDL051	Imperial Oil Resources Limited	10,565
SDL053 to SDL055	Imperial Oil Resources Limited	12,728
SDL058	Imperial Oil Resources Limited	7,168
SDL061	Imperial Oil Resources Limited	4,504
SDL065	Imperial Oil Resources Limited	5,081
SDL083 to SDL088	ConocoPhillips Canada Resources Corp	42,518
SDL089	BP Canada Energy Group ULC	10,512
SDL091 & SDL092-CAN	Imperial Oil Resources Limited	8,573
SDL095	Imperial Oil Resources Limited	11,051
SDL096 & SDL097	ConocoPhillips Canada Resources Corp	1,412
SDL110 to SDL112	Imperial Oil Resources Limited	3,267
SDL113 & SDL114	BP Canada Energy Group ULC	9,582
SDL115 to SDL117	Imperial Oil Resources Limited	6,600
SDL126	ConocoPhillips Canada Resources Corp	16,618
SDL130	Devon NEC Corporation	14,458
SDL132-CAN to SDL136-CAN	MGM Energy	1,050
SDL146-CAN	MGM Energy	507