Arctic Development Roadmap

Final REPORT
R-11-275001-CARD

Prepared for:
Centre for Arctic Resource Development

January 2012

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Version 2

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REVISION HISTORY

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EXECUTIVE SUMMARY

The purpose of this project was to identify, organize and prioritize key research and development (R&D) issues that need to be addressed to fill gaps in the knowledge, technology, methodology and training associated with offshore Arctic oil and gas development. The results of this project are an important input into the five-year research plan for the Centre for Arctic Resource Development (CARD) and highlight research priority areas of relevance to the broader research community and various sectors of the oil and gas industry.

The first task completed was an in-depth literature review of previous Arctic R&D gap assessments. From this review a detailed list of issues was compiled and organized into thematic areas. The second task was the identification of common categories of technology based on development scenarios for Offshore Labrador, Greenland and the Beaufort Sea. The third task involved broad consultation with industry on research and development needs and priorities relating to Arctic resource development. This task was essential in obtaining insights into the relevancy of identified R&D issues to current and long-term industry needs.

The results of the literature review, scenario analysis and industry consultations were synthesized by organizing the list of issues into key R&D themes, and mapping this information to the different categories of technology used throughout various phases of the hydrocarbon development cycle. These issues were then prioritized and organized into the companion chart to this report entitled "The Arctic Development Roadmap R&D Priority Matrix". A priority ranking method was formulated to reflect the relevance of a particular issue to the oil and gas industry. This ranking method also considered the impact of further R&D, anticipated timeframe, extent of applicability (industry-wide or project-specific), and the current state of knowledge for a particular issue. Based on the priority ranking estimates obtained using this method, the top priority R&D issues were identified and summarized.

The top priority issues indentified in this project are:

- **Environmental Protection**. This category includes both emergency scenarios (oil spill prevention and response) and operational considerations (emissions, pollution, noise and environmental footprint). While many important issues were identified within this category, same season well control was identified as the most critical issue.
- **Ice Management**. This category includes detection, monitoring and physical ice management issues. The most critical need identified by industry was in the management of ice to support emergency response. Emphasis was placed on the need for ice management field trials to demonstrate the effectiveness of ice management for different operating conditions, such as detecting and towing multi-year and glacial ice embedded in first-year pack ice.
- **Ice Mechanics and Loading**. This category includes issues related to improving understanding and modeling of ice loads and associated mechanics for different ice-structure interaction scenarios (e.g. ridge loads on sloping structures). The top priority indentified for this category is the collection of full-scale ice load data for large interaction areas (10-100 m^2). Understanding and modeling pack ice pressures and its effects was also identified as a high priority.
- **Station-keeping in Ice**. This category includes issues related to maintaining station during operations in ice using either mooring or dynamic positioning systems. Station-keeping during emergency response was identified as the limiting case used for design. Consequently, the primary R&D issue identified was the need for improved ice load models (and full-scale data) for floating platforms to guide the design of station-keeping systems. The development of mooring systems that allow for reliable, routine operational disconnection under heavy ice loads was also an identified priority.
- **Environmental Characterization**. This category includes issues related to technology and data used in the characterization of ice and metocean conditions, as well as bathymetric, geotechnical, geophysical and other geospatial information. The top priority issue identified in this category was the need for improved technology to allow for rapid, accurate measurement of environmental data both for design and real-time operations.

- **Offshore Safety and Escape, Evacuation, and Rescue**. This category includes issues related to the safety of personnel both in terms of operational safety and during emergency response scenarios. The main priorities identified in this category include the improvement of evacuation craft release, retrieval and personnel transfer methods, as well as improving simulation and training technology used for offshore personnel.
- **Dredging and Trenching**. This category includes technology used to conduct and support dredging/trenching operations. The top priority issues in this category include the need for R&D to reduce the cost of operations, reduce the required burial depth or produce better trenches for arctic pipelines. The development of improved technologies for shallow water dredging/trenching operations was also identified as a priority.
- **Simulation and Training**. This category includes issues related to the development and use of simulation-based tools to evaluate the effectiveness of operational processes, and to assist in the training of personnel. The two main priority areas identified for application of simulation and training technology are in training personnel for escape, evacuation and rescue scenarios, and also for training personnel for oil spill response scenarios.
- **Hydrocarbon Export Technologies**. This category includes different issues associated with delivering produced hydrocarbons to market. The main long-term issue identified in this category was the exploitation of stranded natural gas reserves. Floating liquefied natural gas technology was identified as an export technology of high priority due to its potential applicability in Arctic regions.
- **Arctic Drilling**. This category includes issues related to the drilling and completion of wells in Arctic regions. The top priority issues identified for this category were finding ways to reduce the extremely high cost of drilling in the Arctic and extending the drilling season to enable year-round drilling.

Through R&D efforts focused on the cornerstone issues identified above, advancements in knowledge, technology, methodology and training will enable the development of solutions to key challenges faced by industry. These solutions will play a vital role in overcoming the barriers to Arctic resource development and in enabling the vast hydrocarbon potential of Arctic regions to be realized.

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1 INTRODUCTION

1.1 Purpose

The purpose of this project was to develop an "Arctic Development Roadmap" (ADR) to identify, organize and prioritize key R&D themes needed to fill gaps in the knowledge, technology, methodology and training associated with offshore Arctic oil and gas development. In this study, onshore facilities are not considered, except where needed to support offshore operations. As indicated in Figure 1-1 below, the results of this project are an important input into the five-year research plan for the Centre for Arctic Resource Development (CARD) and also highlight research priority areas of relevance to the broader research community and various sectors of the oil and gas industry.

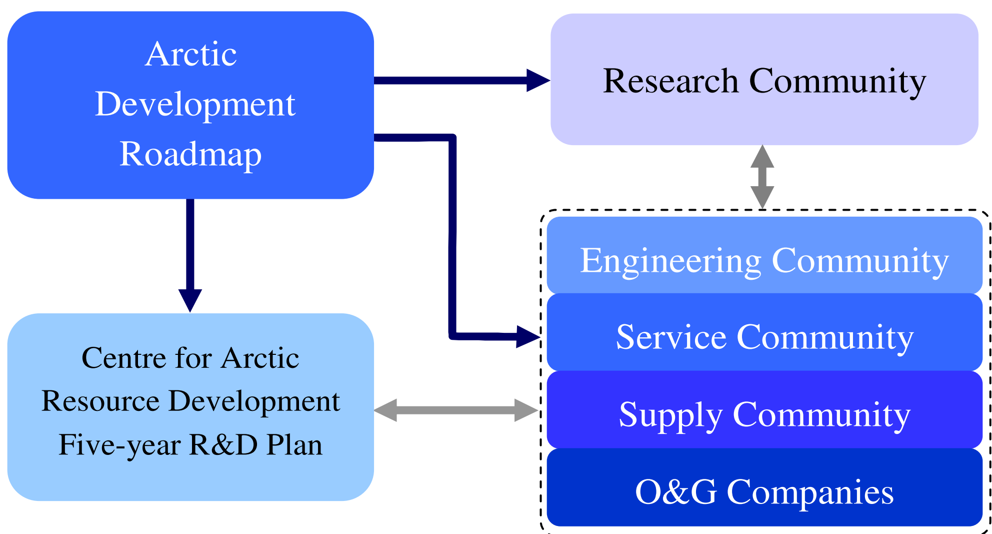


Figure 1-1. Linkages between the Arctic Development Roadmap project, CARD and the broader technical community

The aim of the ADR project is to stimulate strategic long and medium-term R&D initiatives to support oil and gas development in harsh, northern environments. It is noted that throughout this report the term 'Arctic' is used broadly to refer to all offshore regions where ice conditions are present either seasonally or year-round, including sub-Arctic regions such as the Grand Banks.

1.2 The Arctic Development Landscape

The physical environment in northern regions presents unique challenges which increase the complexity and cost of offshore oil and gas development. These conditions include:

- Low temperatures
- Sea ice (including extreme ice features up to 30 m thick)
- Icebergs and/or ice islands
- Ice scour of the seabed
- Permafrost and icing
- Seabed hazards, including gas hydrates and shallow gas
- Winter darkness (particularly for high latitudes)
- Weak soil and seabed conditions

Despite the many challenges posed by such harsh environmental conditions, industry has developed feasible solutions for production in fields in marginal sea ice, and iceberg environmental zones such as the Grand Banks. Further north, in regions such as the Beaufort Sea, industry has also developed capabilities to safely conduct exploratory drilling through permafrost and offshore out to about 30 m using year-round fixed platforms and deeper using drillships during the summer and early winter (Croasdale and McDougall, 1992). Through the use of ice management vessels, operators have effectively been able to extend the drilling window beyond the open water season. In regions with deeper water and heavier ice conditions the drilling seasons are considerably shorter, and multi-season drilling campaigns may be required to finish drilling a single exploration well. While exploration timelines may be spread over multiple seasons, as the development cycle moves towards production it will become necessary to drill multiple wells per season and operate year-round to enable economic production. As hydrocarbon activity moves farther north, a step change in knowledge, methodology and technology is required to enable safe and economic offshore developments in these regions.

From a holistic perspective, there are many other challenges that must also be overcome to enable operations in these regions. The Arctic development landscape is complex and multidimensional. As indicated in Figure 1-2, economic, technical, human factors, regulatory, socio-economic, environmental and geopolitical dimensions must be considered. Convergence of these different paths must occur for Arctic resource development to become a reality. To enable this, gaps between these different dimensions must be bridged and major development barriers in each sector must be overcome.

Research and development has a vital role to play in helping fill gaps in knowledge and understanding, technology and methodology, as well as training requirements, which need to be addressed to overcome these development barriers.

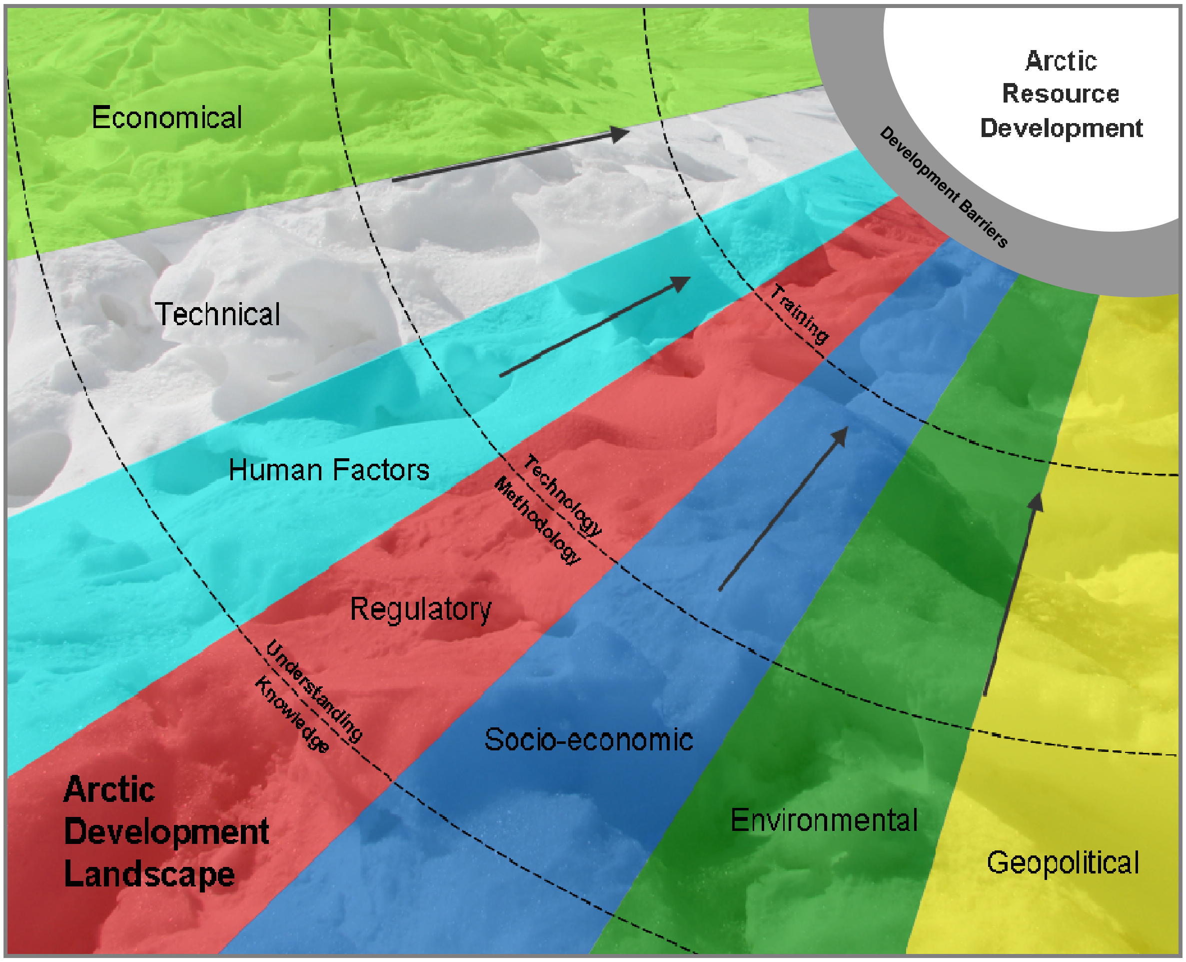


Figure 1-2. Illustration of the multi-dimensional nature of the Arctic development landscape

For researchers working on Arctic issues, consideration of this multi-dimensional environment is important. Solutions which simultaneously satisfy the requirements of all development facets are much more favorable than those produced in isolation, which may have unintended, complicating consequences in other sectors of the development landscape.

1.3 Centre for Arctic Resource Development (CARD)

The C-CORE Centre for Arctic Resource Development (CARD) aims to build a mass of Arctic R&D expertise and position Newfoundland and Labrador as a centre of technological excellence for northern oil and gas development. CARD will create more than 20 new full-time positions for highly qualified individuals, from current world-class experts to rising research stars.

With base funding of $12.5 million over five years ($2.5M per year) from the Hibernia and Terra Nova projects, CARD conducts medium to long-term R&D designed to improve the capacity and capability for safe, responsible and cost-effective hydrocarbon development in Arctic and sub-Arctic regions. As discussed in Section 1.1, the ADR is an important input into the CARD five-year R&D plan that is vetted by industry. The centre's expertise will be primarily engineering, though it will interface with experts in many fields, both industry and academia, with a goal of developing the knowledge, tools, technologies, methodologies and highly-qualified people needed for Arctic offshore hydrocarbon development.

1.4 Project Objectives

The main objectives of the ADR project are as follows:

1. Identify gaps in the knowledge, technology, methodology and training needed for offshore oil and gas development in Arctic and sub-Arctic regions.
2. Develop an industry-vetted list of R&D priorities to address Arctic development issues.
3. Develop a companion chart to this report, "The Arctic Development Roadmap R&D Priority Matrix" to aid with the definition of appropriate R&D thrusts and provide information to support the development the CARD 5-year R&D plan.
4. Promote a better understanding of R&D priorities throughout the broader technical community.

1.5 Methodology

A three-pronged approach was used to develop the Arctic Development Roadmap:

1. A detailed literature review was conducted to determine what issues have been identified from earlier studies.
2. Selected Arctic development scenarios were evaluated to identify the main categories of technology associated with different stages of an Arctic development project.
3. Industry representatives, regulators and other subject matter experts were consulted to gather opinions on R&D priorities based on industry needs.

As illustrated in Figure 1-3, the results from the first two tasks were used as the basis of discussions carried out during the industry consultation phase. The results from all three tasks were subsequently synthesized into the 'Arctic Development Roadmap' Summary Report and its companion R&D Priority Chart, which maps out the prioritized R&D themes identified by industry. These tools are meant to help guide decision-making for research programs focused on addressing the needs of the Arctic offshore oil and gas sector.

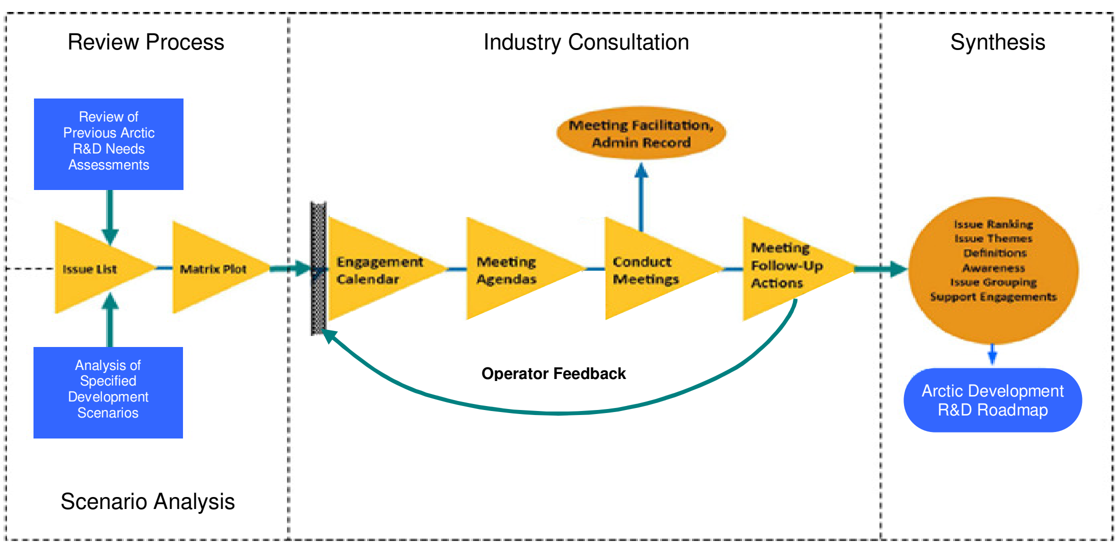


Figure 1-3. Overview of research methodology used (modified after Pavia et al; 2011)

Additional details of the review process and scenario analysis are provided in Chapter 2 and Chapter 3, respectively. The industry consultation and synthesis results are summarized in Chapter 4.

2 REVIEW OF PREVIOUS R&D ASSESSMENTS

2.1 Overview of Approach

An in-depth literature review of the reports summarized in Table 2-1was performed to identify previously assessed issues relating to Arctic resource 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.

2.2 Categories of Identified R&D Issues

A detailed list of Arctic R&D issues was generated from the literature review and compiled into a master list. While the full details of this literature review are beyond the scope of this report, it was concluded that Arctic resource development issues could be grouped into the following main categories:

- **Environmental characterization** issues are associated with the challenges related to the characterization of regional ice and metocean conditions considered for design and operations in Arctic environments. This area also includes challenges related to collection and analysis of bathymetric and other data such as basin geology, geophysics, and geospatial data.

- **Ice-structure interactions** issues are associated with ice mechanics, ice feature strength and load modeling and relate to the collection and analysis of ice load data, modeling of ice failure processes and estimation of ice loads for different ice-structure interaction scenarios. This also includes issues with floating structures such as station-keeping and maintaining position under ice loading for both operational and emergency response (limiting case) situations.

- **Subsea issues** are those related primarily to interactions of deep draft ice features with the seabed, pipelines, and other subsea equipment. This category also includes ensuring the integrity of subsea assets and protecting them from interactions with ice.

- **Ice management** issues are those related to the detection, monitoring, and physical management of glacial and sea ice features, including the use of disconnectable turrets on floating structures to mitigate risk of impact.

- **Environmental protection** issues include those related to same season well control (e.g. relief well) and spill prevention and response issues. In addition to emergency response scenarios (e.g. explosion, blowout, grounding, or collision), this category also includes operational issues (e.g. noise and emission, environmental footprints).

- **Engineering and design** issues refer to challenges associated with engineering and design methods, codes and standards for ships, structures, and system components for Arctic conditions. This category includes issues with foundations and permafrost.

- **Hydrocarbon export** issues are those associated with bringing produced hydrocarbons to market, which includes pipelines, landfalls, and dredging/trenching issues, as well as those associated with export tankers and alternative gas export technologies.

- **Offshore safety and human factors** issues include those challenges related to Escape, Evacuation and Rescue (EER), as well as those related to safe work environments (e.g. noise, vibration, illumination, icing on work surfaces) and safe operations (e.g. safety inspections and equipment performance monitoring). This category also includes issues related to human performance, decision-making, and ergonomics in harsh/cold conditions, and simulation/training activities required for safe Arctic operations.

- **Logistics, infrastructure and support** issues are related to the availability of resources (e.g. personnel, supplies) and time/scheduling to support operations. This category spans all phases of development and includes operational and emergency response scenarios.

- **Drilling and Operations** issues are those challenges related to drilling, completion and intervention in cold climates, including geohazards such as permafrost, shallow gas, and gas hydrates. Includes allowances for access to well by drill rig for work-over operations. Operational challenges include those associated with operating equipment (e.g. electrical and mechanical systems) in cold, remote climates. This includes material selection, maintenance, routine inspections, and intervention to ensure asset integrity and flow assurance.

The above information was combined with the results of the development scenario analysis (described in Chapter 3) to form the basis of the discussion list used during the industry consultation phase. Synthesis of the information collected from the literature review into the final analysis is discussed in Chapter 4.

3 DEVELOPMENT SCENARIO ANALYSIS

3.1 Overview

The purpose of this section is to review hydrocarbon development scenarios for selected Arctic regions to allow for identification of the key categories of technology, knowledge and methodology required throughout different stages of the oil and gas development life-cycle. As summarized in Figure 3-1, the development life-cycle consists of several distinct multi-year phases. This process is typical of offshore developments and in practice such projects are managed using a stage-gate approach.

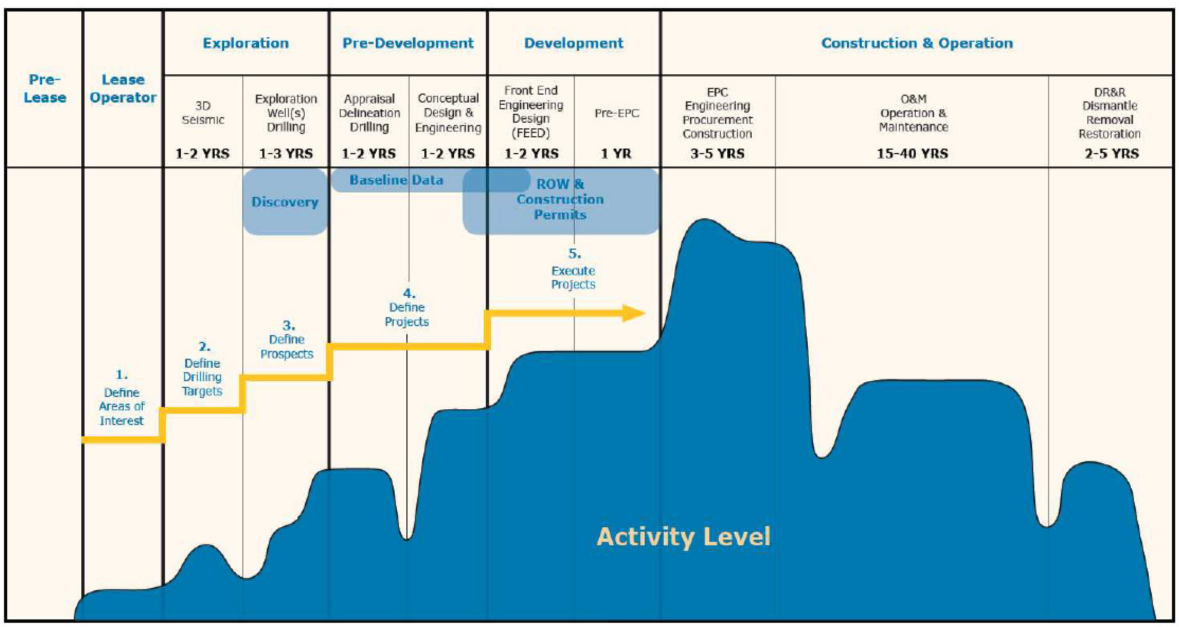


Figure 3-1. Overview of development life-cycle for an Arctic oil and gas project (Pavia et al; 2011)

Other factors such as the current state of knowledge, technology, and other development dimensions discussed in Chapter 1 can have significant impacts on this cycle. For instance, the time to obtain regulatory approval in some regions may be longer than the estimates provided in Figure 3-1.

To highlight different activities associated with the phases of an offshore Arctic project, a summary of the key steps are presented in Figure 3-2. These activities are considered in the context of regional development scenarios in the ensuing section.

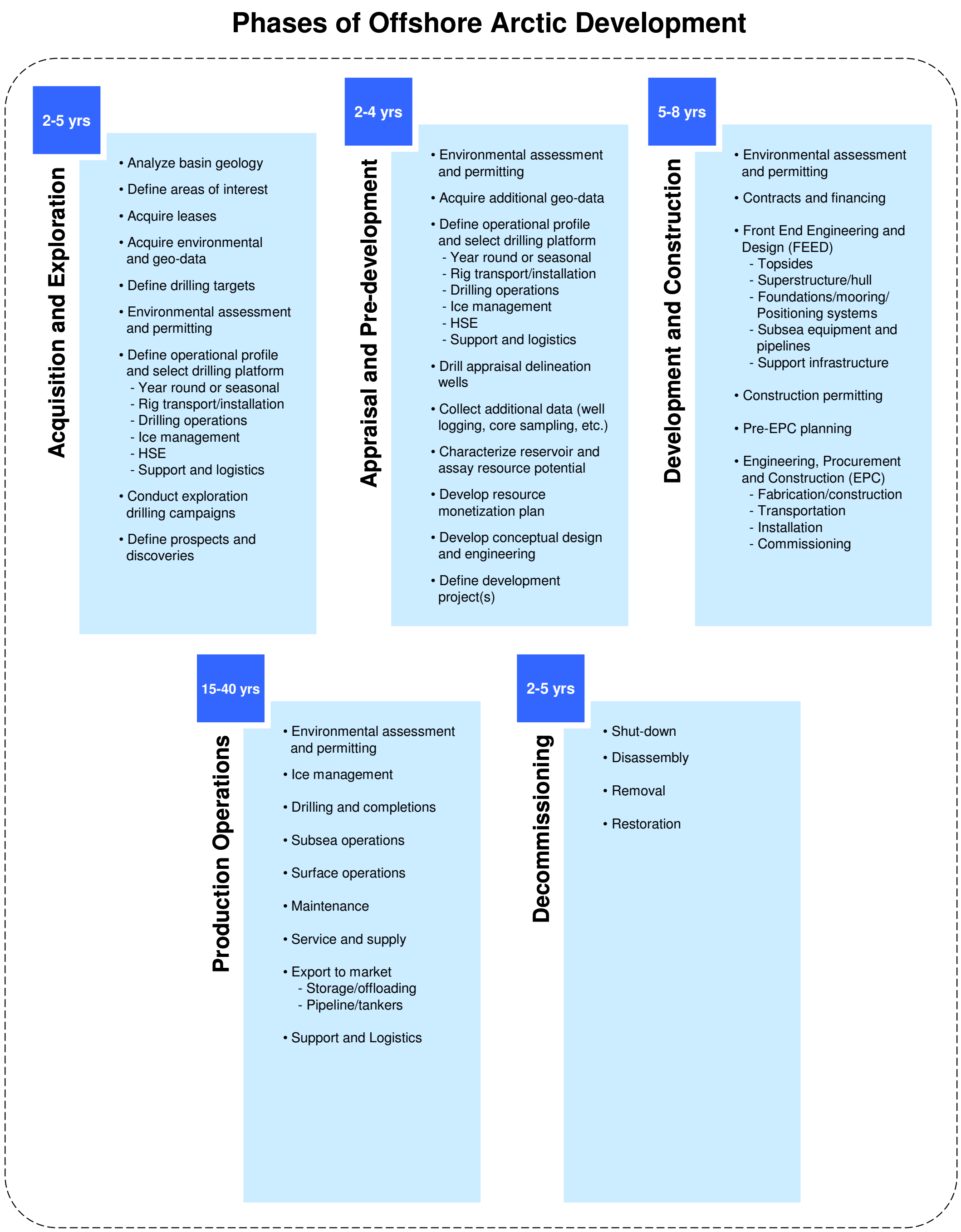


Figure 3-2. Activities associated with different development stages for an arctic oil and gas project

3.2 Development Scenarios for Selected Regions

To assist in the identification of technology needed for different Arctic regions, several different development scenarios are examined below. In focusing on common issues, the aim is to identify opportunities for R&D that will offer potential benefits that are industry-wide, rather than unique to a particular project or region.

In the present analysis it is assumed that the development of hydrocarbon resources will occur in a sequence which reflects the degree of difficulty associated with operating in a given geographical region. As shown in Figure 3-3, Arctic regions may be grouped into three levels of development difficulty: moderate, high and extreme. Advances in engineering and technology during the 1980s and 1990s enabled the development of projects in sub-Arctic regions such as the Grand Banks and Sakhalin. Through these and other projects in harsh offshore environments, the oil and gas industry has gained much valuable experience.

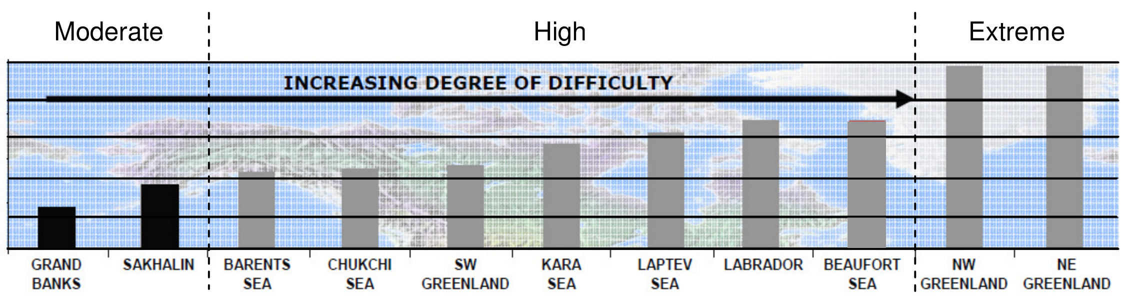


Figure 3-3. Relative degree of difficulty for development of different Arctic regions (modified from Scott, 2009)

As offshore developments move farther north into more challenging environments, additional research and development will be needed to address issues that arise. Leveraging experience gained from existing operations in sub-Arctic regions will be essential in the development of more difficult regions.

For the timeframes of interest for this report (i.e. 10-20 year development window), it is assumed that the majority of industry activity will be concentrated in regions such as the Barents Sea, Chukchi Sea, Southwest Greenland, Kara and Laptev Seas, Labrador and the Beaufort Sea. Regions such as Northwest and Northeast Greenland represent some of the most formidable and challenging environments in the world. Prior to developing resources in such 'extreme' conditions, solutions should first be developed and validated for less severe conditions. For example, icebergs in pack ice are an important consideration for Northwestern and Northeastern Greenland, Labrador, the Barents Sea, the Kara Sea, the Laptev Sea, Southwest Greenland and the Grand Banks (typically no pack ice). While the severity of ice conditions may vary from region to region, the development of solutions for towing icebergs in pack ice in Labrador, for instance, could be directly applied to other regions. Similarly, in the Beaufort Sea, multi-year ice features are a dominant design consideration. Solutions developed for the severe multi-year ice conditions of the Beaufort Sea will also be applicable to other regions dominated by similar (or less severe) sea ice conditions.

Based on the above rationale, selected development scenarios have been defined for three regions: Southwest Greenland, Labrador, and the Beaufort Sea. While there are many possible combinations of different technologies that may be employed in the development of a given hydrocarbon field, the conditions outlined in Table 3-1 below are meant to provide a representative sampling of the main challenges faced in a typical Arctic development project. Details of the environmental conditions for each region and the associated development scenario(s) noted above are summarized below.

Table 3-1. Summary of development scenarios considered

Scenario Description					Environmental Conditions				
ID No.	Region	Type	Structure Type	Export Method	Water Depth (m)	First-Year Ice	Multi-Year Ice	Icebergs	Ice Islands
1	**Labrador**	Gas	FLNG	LNG Tankers	100-300	✓	✓	✓	✓
2	**SW Greenland**	Oil	FPSO	Shuttle Tankers	100-400	✓	✓	✓	✓
3	**Beaufort Sea**	Oil	Fixed Platform	Shuttle Tankers	< 100	✓	✓		✓
4	**Beaufort Sea**	Gas	Fixed Platform	Pipeline	< 100	✓	✓		✓
5	**Beaufort Sea**	Oil	Floating Structure	Tieback to Offloading Facility, Tankers	100-1000	✓	✓		✓

Given the lack of pipeline infrastructure in the Arctic, marine export is assumed for all scenarios except Case 4 which is based on the assumption that a major Arctic pipeline, such as the Mackenzie pipeline, is developed to provide access to markets for Arctic gas.

3.2.1 Labrador Development Scenarios

As indicated in Figure 3-4 there are several active offshore oil and gas license agreements for the Labrador shelf. This region is characterized by heavy pack ice and contains first-year ice, multi-year ice, icebergs, ice islands and high wave conditions in summer. Details of the environmental characteristics of Labrador are included in Appendix A.

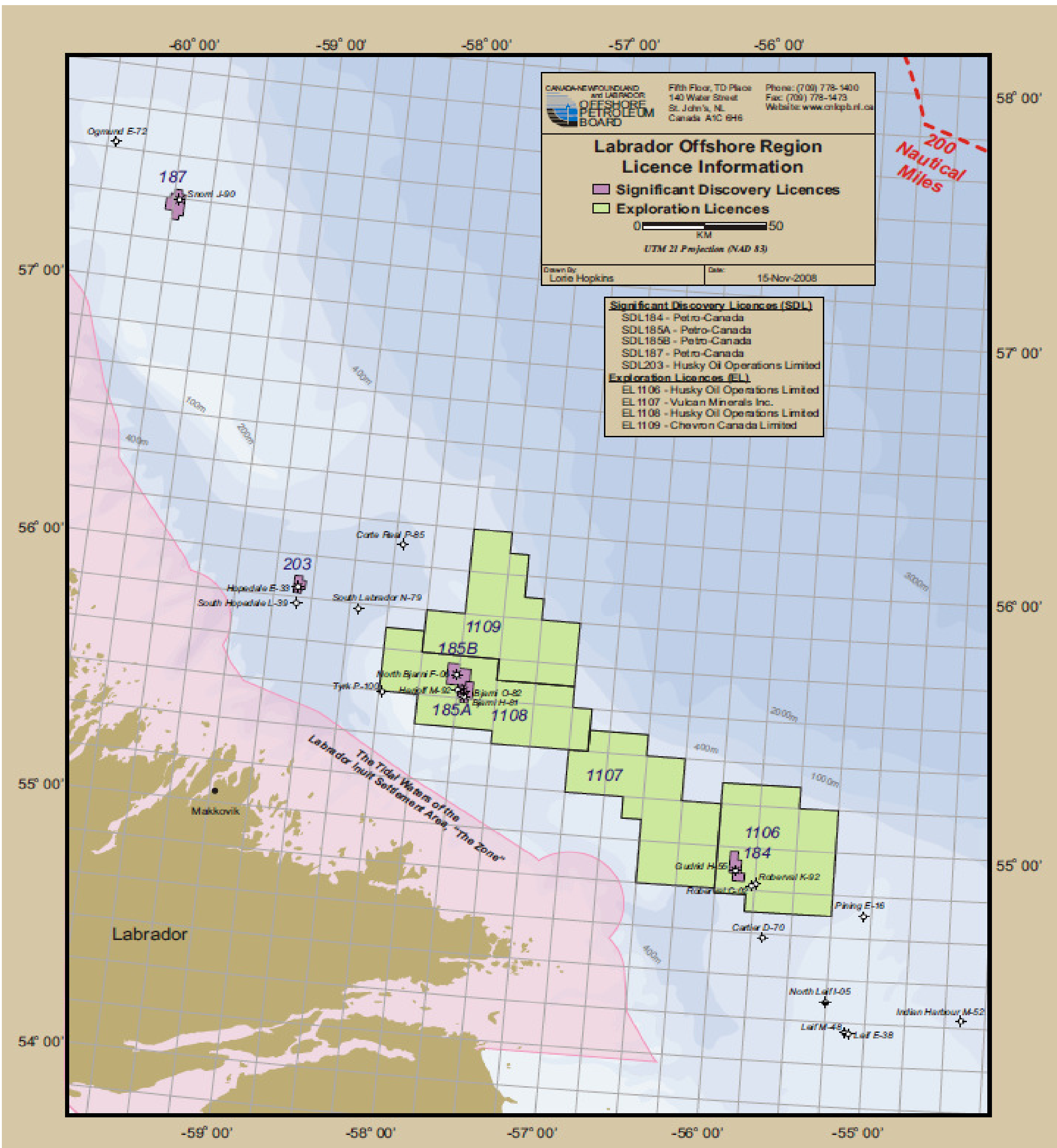
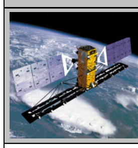
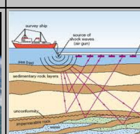
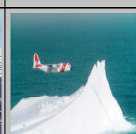
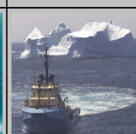
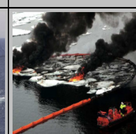
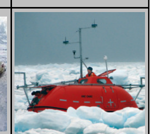
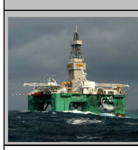
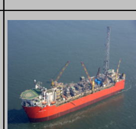
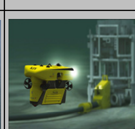
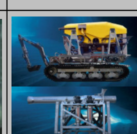
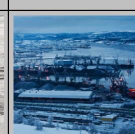
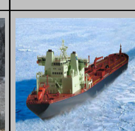


Figure 3-4. Active license agreements for offshore Labrador

Since natural gas is the primary resource discovered to date in this region, it is assumed that a gas development would be most probable for the Labrador Shelf (100-300m). Based on the associated environmental conditions and recent advances in floating liquefied natural gas (FLNG) technology, the development described below is based on use of a disconnectable Arctic Class FLNG production platform with Ice Management support and Arctic Class LNG tankers to deliver the gas to market. From an analysis of the activities corresponding with each phase of such a development and the associated technologies required, the main categories of technology required for such a development have been summarized in Table 3-2.

Table 3-2. Categories of technology required for a potential Labrador gas development

Hydrocarbon Detection, Exploration and Evaluation Technology			Ice Management Technology		Environmental Protection Technology		Escape, Evacuation and Rescue
Surface Detection and Remote Sensing	Seismic Technology	Drilling and Well Evaluation	Ice Detection/Monitoring Technology	Physical Ice Management	Spill Prevention and Response	Emissions and Pollution Control	EER Technologies
							
Includes tools and technologies for field mapping, analysis of seeps, satellite imagery, gravity surveys and magnetic surveys.	Tools for evaluation of frontier basin geology and hydrocarbon potential, mapping seabed, including collection in ice conditions; 2D, 3D, 4D seismic technology.	Includes technologies for drilling and directly supporting drilling operations in Arctic environments, well control technologies and tools for well logging (e.g. wire-line, mud or memory log).	Include technologies for surveillance and monitoring of environmental conditions (e.g. satellites, aerial surveillance, AUVs, UAVs, ship-based systems and various radar technologies).	Includes technologies for deployment and handling of tow ropes and nets, and techniques for management of sea ice, icebergs or other ice features.	Includes technologies for preventing, containing and responding to oil spills in Arctic conditions; includes well control and containment technologies, and those for cleaning-up and dispersing oil in ice.	Includes technologies for preventing pollution and controlling emissions and noise due to operations in Arctic environment (including support vessels).	Includes technologies, processes and models that promote effective escape, evacuation and rescue procedures from an installation located in an Arctic environment.
Platform Technology: Floating Structures		Subsea Technology		Transportation and Support Technology		Hydrocarbon Export Technology	
Semi-submersibles	FPSO	Subsea Production and Protection Equipment	Dredging and Trenching	Icebreakers and Support Vessels	Ports and Infrastructure	Pipelines	Tankers and Gas Export Alternatives
							
Semi-submersible drill rigs used for seasonal drilling in Arctic environments.	Includes ship-shaped and round hull floating production storage offloading (FPSO) vessels, floating production units (FPU), floating storage offloading (FSO) and floating liquid natural gas (FLNG) vessels.	Includes subsea equipment, well head, risers, flowlines, umbilicals, subsea communications, robotics, subsea drilling and subsea protection issues (glory holes, structures, breakaway flowlines and couplings, etc.).	Includes Arctic-capable dredging technologies for use in construction of berms, foundations, and glory holes; trenching includes issues with pipeline trenching and burial in soil, rock and permafrost.	Includes icebreakers, and ice class support ships and tugs needed to support offshore operations.	Includes port facilities, navigation aids and markers, refueling depots, and other supporting facilities.	Includes pipe-laying methodology suitable for Arctic environments, pipeline design issues, route selection and pipelines protection strategies.	Includes tankers capable of operations in ice environments; includes double acting tankers and other gas export alternative technologies such as floating liquefied natural gas (FLNG) or compressed natural gas (CNG).

The above results are compared with those obtained from other Arctic development scenarios later in this chapter to identify those common to all regions.

3.2.2 Greenland Development Scenarios

As indicated in Figure 3-5, there are presently active exploration licenses throughout Western and Southwestern Greenland. Land sales have occurred for Northwestern Greenland as well, but these areas are not currently being actively explored. This region is characterized by icebergs, first-year ice with occasional multi-year ice inclusions, and occasional ice islands. High wave conditions can occur, particularly during the open water drilling season. A detailed summary of the environmental characteristics of Greenland are included in Appendix A.

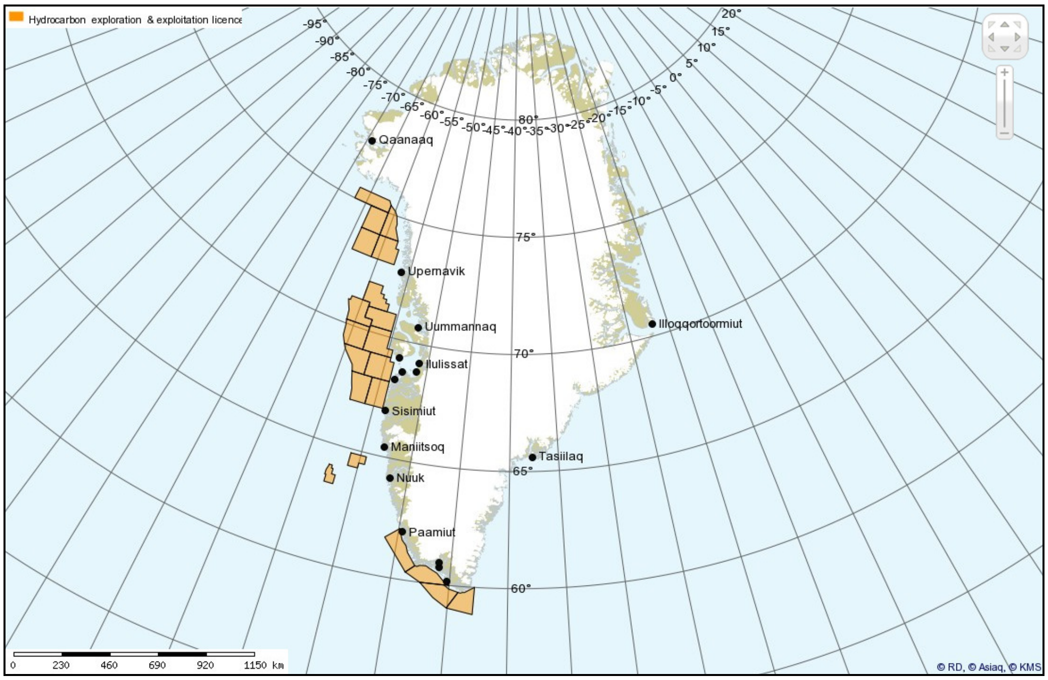
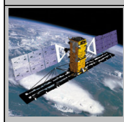
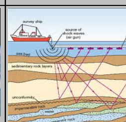
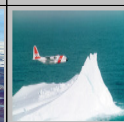
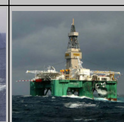
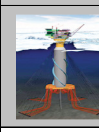
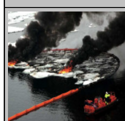
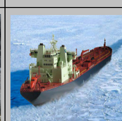
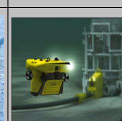
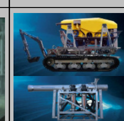
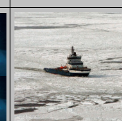


Figure 3-5. Greenland active exploration licenses

Given the current and anticipated exploration activities in Greenland, the selected scenario for this region is an oil development, not natural gas. It is assumed that any produced gas could be either used to supply energy for operations or re-injected to enhance oil recovery. A disconnectable floating platform is likely for the heavy ice conditions in this region and the scenario outlined here is based on an Arctic Class Floating Production Storage Offloading (FPSO) vessel with ice management support. To deliver oil produced in Greenland either directly to market or to an ice-free transshipment facility, such as the one in southern Newfoundland, Arctic Class oil tankers would be required. Based on an analysis of the activities corresponding with each phase of such a development, the main categories of technology required for this type of development are summarized in Table 3-3.

Table 3-3. Categories of technology required for a potential Greenland oil development

Hydrocarbon Detection, Exploration and Evaluation Technology			Ice Management Technology		Platform Technology: Floating Structures			
Surface Detection and Remote Sensing	Seismic Technology	Drilling and Well Evaluation	Ice Detection/Monitoring Technology	Physical Ice Management	Semi-submersibles	Tension Leg Platform (TLP)	FPSO	SPAR
								
Includes tools and technologies for field mapping, analysis of seeps, satellite imagery, gravity surveys and magnetic surveys.	Tools for evaluation of frontier basin geology and hydrocarbon potential, mapping seabed, including collection in ice conditions; 2D, 3D, 4D seismic technology.	Includes technologies for drilling and directly supporting drilling operations in Arctic environments, well control technologies and tools for well logging (e.g. wire-line, mud or memory log).	Include technologies for surveillance and monitoring of environmental conditions (e.g. satellites, aerial surveillance, AUVs, UAVs, ship-based systems and various radar technologies).	Includes technologies for deployment and handling of tow ropes and nets, and techniques for management of sea ice, icebergs or other ice features.	Semi-submersible drill rigs used for seasonal drilling in Arctic environments.	Includes conceptual multi-leg and single leg platform designs proposed for deepwater Arctic regions.	Includes ship-shaped and round hull floating production storage offloading (FPSO) vessels, floating production units (FPU), floating storage offloading (FSO) and floating liquid natural gas (FLNG) vessels.	Includes conceptual ice-class SPAR designs (single or multiple cell).
Environmental Protection Technology		Escape, Evacuation and Rescue	Hydrocarbon Export Technology		Subsea Technology		Transportation and Support Technology	
Spill Prevention and Response	Emissions and Pollution Control	EER Technologies	Pipelines	Tankers and Gas Export Alternatives	Subsea Production and Protection Equipment	Dredging and Trenching	Icebreakers and Support Vessels	Ports and Infrastructure
								
Includes technologies for preventing, containing and responding to oil spills in Arctic conditions; includes well control and containment technologies, and those for cleaning-up and dispersing oil in ice.	Includes technologies for preventing pollution and controlling emissions and noise due to operations in Arctic environment (including support vessels).	Includes technologies, processes and models that promote effective escape, evacuation and rescue procedures from an installation located in an Arctic environment.	Includes pipe-laying methodology suitable for Arctic environments, pipeline design issues, route selection and pipelines protection strategies.	Includes tankers capable of operations in ice environments; includes double acting tankers and other gas export alternative technologies such as floating liquefied natural gas (FLNG) or compressed natural gas (CNG).	Includes subsea equipment, well head, risers, flowlines, umbilicals, subsea communications, robotics, subsea drilling and subsea protection issues (glory holes, structures, breakaway flowlines and couplings, etc.).	Includes Arctic-capable dredging technologies for use in construction of berms, foundations, and glory holes; trenching includes issues with pipeline trenching and burial in soil, rock and permafrost.	Includes icebreakers, and ice class support ships and tugs needed to support offshore operations.	Includes port facilities, navigation aids and markers, refueling depots, and other supporting facilities.

3.2.3 Beaufort Sea Development Scenarios

Much of the industry activity in the Beaufort Sea to date has been concentrated in the continental shelf region (< 100 m), though there are several lease blocks in the deeper waters of the continental slope (100-1000 m). Presently there are active exploration leases in both the U.S. Beaufort Sea (Figure 3-6) and the Canadian Beaufort Sea (Figure 3-7). The severity of the ice conditions varies throughout the region, and depends on the density of multi-year ice features embedded in the pack ice. Of most interest to design are extreme ice features such as large multi-year ridged ice as well as occasional ice islands and ice island fragments. Heavy first-year sea ice and pack ice pressures are also important considerations for operations in this region. Details of the environmental characteristics of the Beaufort Sea region are included in Appendix A.

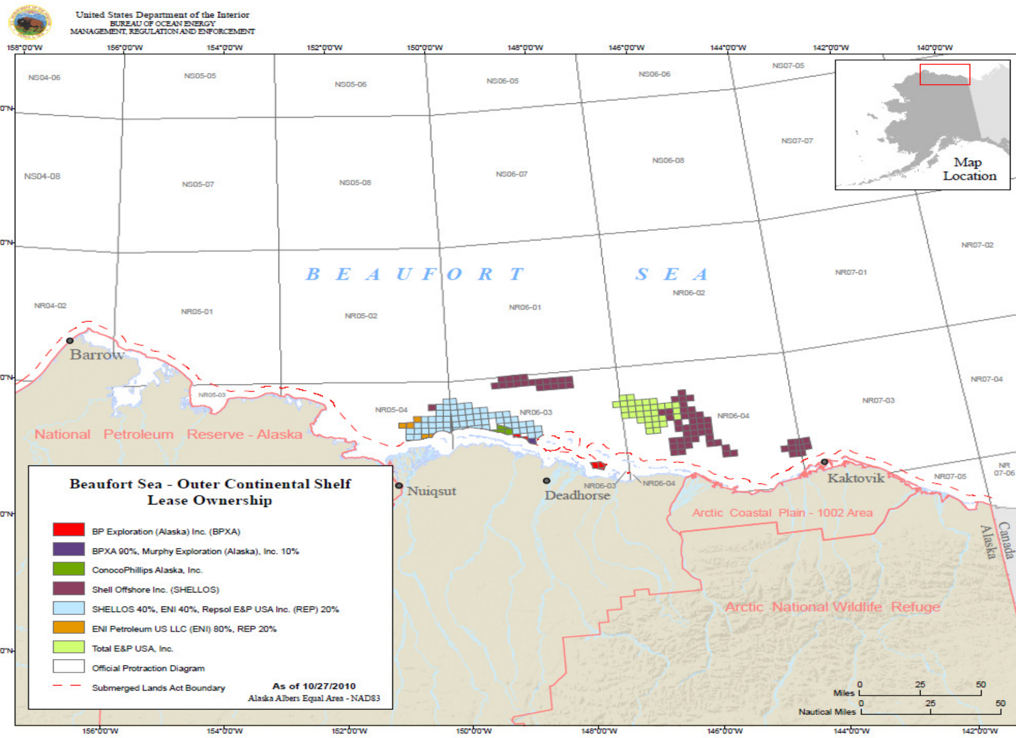


Figure 3-6. US Beaufort offshore oil and gas licenses

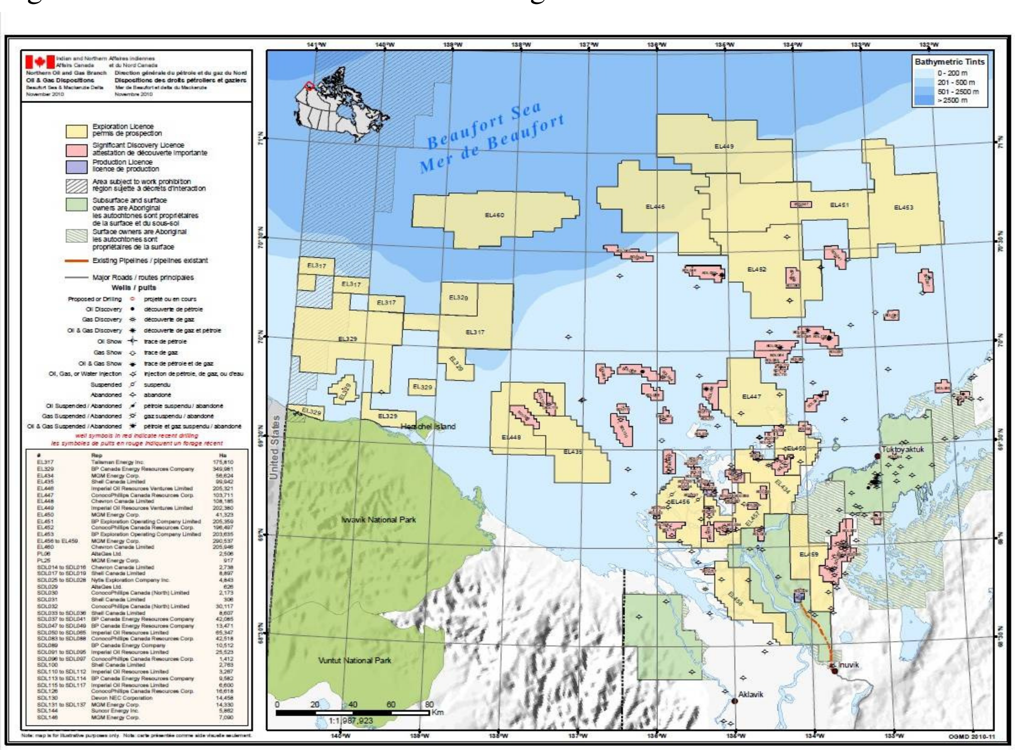
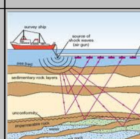
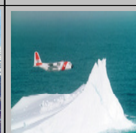
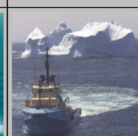
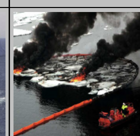
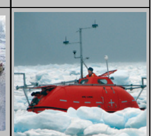
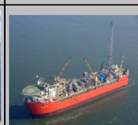
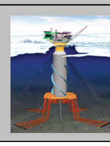
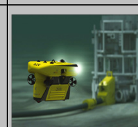
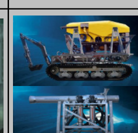
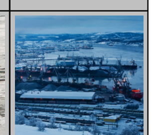
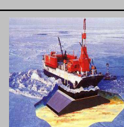
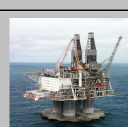


Figure 3-7. Canadian Beaufort offshore oil and gas licenses

Based on the high levels of offshore activity in this region, three possible scenarios are considered for this region: an on-shelf (< 100 m) oil development, an on-shelf (< 100 m) natural gas development, and an oil development on the continental slope (100-1000 m).
A detailed analysis of the different technologies was conducted for each of these scenarios, and the main categories of technology required for these development scenarios is summarized in Table 3-4 below.

Table 3-4. Categories of technology required for potential Beaufort Sea developments

Hydrocarbon Detection, Exploration and Evaluation Technology			Ice Management Technology		Environmental Protection Technology		Escape, Evacuation and Rescue
Surface Detection and Remote Sensing	Seismic Technology	Drilling and Well Evaluation	Ice Detection/Monitoring Technology	Physical Ice Management	Spill Prevention and Response	Emissions and Pollution Control	EER Technologies
							
Includes tools and technologies for field mapping, analysis of seeps, satellite imagery, gravity surveys and magnetic surveys.	Tools for evaluation of frontier basin geology and hydrocarbon potential, mapping seabed, including collection in ice conditions; 2D, 3D, 4D seismic technology.	Includes technologies for drilling and directly supporting drilling operations in Arctic environments, well control technologies and tools for well logging (e.g. wire-line, mud or memory log).	Include technologies for surveillance and monitoring of environmental conditions (e.g. satellites, aerial surveillance, AUVs, UAVs, ship-based systems and various radar technologies).	Includes technologies for deployment and handling of tow ropes and nets, and techniques for management of sea ice, icebergs or other ice features.	Includes technologies for preventing, containing and responding to oil spills in Arctic conditions; includes well control and containment technologies, and those for cleaning-up and dispersing oil in ice.	Includes technologies for preventing pollution and controlling emissions and noise due to operations in Arctic environment (including support vessels).	Includes technologies, processes and models that promote effective escape, evacuation and rescue procedures from an installation located in an Arctic environment.
Platform Technology: Floating Structures				Subsea Technology		Transportation and Support Technology	
Semi-submersibles	Tension Leg Platform (TLP)	FPSO	SPAR	Subsea Production and Protection Equipment	Dredging and Trenching	Icebreakers and Support Vessels	Ports and Infrastructure
							
Semi-submersible drill rigs used for seasonal drilling in Arctic environments.	Includes conceptual multi-leg and single leg platform designs proposed for deepwater Arctic regions.	Includes ship-shaped and round hull floating production storage offloading (FPSO) vessels, floating production units (FPU), floating storage offloading (FSO) and floating liquid natural gas (FLNG) vessels.	Includes conceptual ice-class SPAR designs (single or multiple cell).	Includes subsea equipment, well head, risers, flowlines, umbilicals, subsea communications, robotics, subsea drilling and subsea protection issues (glory holes, structures, breakaway flowlines and couplings, etc.).	Includes Arctic-capable dredging technologies for use in construction of berms, foundations, and glory holes; trenching includes issues with pipeline trenching and burial in soil, rock and permafrost.	Includes icebreakers, and ice class support ships and tugs needed to support offshore operations.	Includes port facilities, navigation aids and markers, refueling depots, and other supporting facilities.
Platform Technology: Bottom-founded Structures				Hydrocarbon Export Technology			
Man-made Islands	Barge/Vessel	GBS	Jacket/ Monopod / Jack-up Rig	Pipelines	Tankers and Gas Export Alternatives		
							
Includes conceptual ice-class SPAR designs (single or multiple cell).	Includes piled or ballasted structures; may be on a berm.	Includes concrete structure, such as Hibernia, and steel GBS concepts.	Jacket and Monopod structures such as those used in Cook Inlet. Includes strengthened jack-up for seasonal use during open water season.	Includes pipe-laying methodology suitable for Arctic environments, pipeline design issues, route selection and pipelines protection strategies.	Includes tankers capable of operations in ice environments; includes double acting tankers and other gas export alternative technologies such as floating liquefied natural gas (FLNG) or compressed natural gas (CNG).		

3.3 Common Categories of Technology Required for Arctic Developments

Based on the scenario analysis, the main categories of technology required for Arctic oil and gas development include:

Hydrocarbon Detection, Exploration and Evaluation Technologies
This category includes technology relating to surface detection and remote sensing, seismic technology and drilling and well evaluation. Surface detection and remote sensing includes tools and technologies for field mapping, analysis of seeps, satellite imagery, gravity surveys and magnetic surveys. Seismic technology includes tools for evaluation of frontier basin geology and hydrocarbon potential. Seismic technology also involves seabed mapping, including collection in ice conditions and 2D, 3D, 4D seismic technologies. Drilling and well evaluation includes technologies for drilling and directly supporting drilling operations in Arctic environments, well control technologies and tools for well logging (e.g. wire line, mud or memory log).

Ice Management Technologies
This covers technology relating to ice detection and monitoring and physical ice management. Ice detection and monitoring includes technologies for surveillance and monitoring of environmental conditions (e.g. satellites, aerial surveillance, AUVs, UAVs, ship-based systems and various radar technologies). Physical ice management includes technologies for deployment and handling of tow ropes and nets, and techniques for management of sea ice, icebergs or other ice features.

Bottom-founded Structure Platform Technologies
This category includes technology relating to man-made islands, barges and gravity based structures (GBS). Man made islands include rock/sand/gravel islands, caisson retained islands and ice islands. Barge structures include piled or ballasted structures which may be situated on a berm. GBS concepts include technologies related to both concrete and steel gravity based structures. Jacket Structure technologies include those relating to strengthened jack-up structures for seasonal use during open water seasons as well as jacket and monopod structures.

Floating Structure Platform Technologies
This group includes technology relating to Floating Production Storage Offloading (FPSO) systems, semi-submersibles, Tension Leg Platforms (TLP) and SPAR platforms. FPSOs include ship-shaped and round hull FPSO vessels, Floating Production Units (FPU), Floating Storage Offloading (FSO) and Floating Liquefied Natural Gas (FLNG) vessels. Semi-submersibles include drill rigs used for seasonal drilling in Arctic environments. TLPs include conceptual multi-leg and single leg platform designs

proposed for deepwater Arctic regions and SPAR platforms include conceptual ice-class SPAR designs (single or multiple cells).

Subsea Technologies

This category includes technology relating to subsea production, protection, dredging and trenching. Subsea production and protection equipment includes subsea equipment, well head, risers, flow-lines, umbilicals, subsea communications, robotics, subsea drilling, and subsea protection issues (glory holes, structures, breakaway flowlines and couplings, etc.) Dredging and trenching includes tools and technologies for Arctic-capable dredging for use in construction of berms, foundations, and glory holes as well as issues with pipeline trenching and burial in soil, rock and permafrost.

Hydrocarbon Export Technologies

Technologies relating to pipelines, tankers and gas export alternatives are included in this group. Pipelines include tools and technologies related to pipe-laying methodologies suitable for Arctic environments, pipeline design issues, route selection and pipelines protection strategies. Tankers and gas export alternative technologies include tankers capable of operations in ice environments, whether having ice breaking capability (double acting tanker) or requiring icebreaker support, and other gas export alternative technologies such as FLNG or compressed natural gas (CNG).

Transportation and Support Technologies

This category is comprised of technology relating to icebreakers and support vessels as well as ports and infrastructure. Icebreakers and support vessels involve tools and technologies relating to icebreakers, ice class support ships and tugs needed to support offshore operations. Ports and infrastructure include port facilities, navigation aids and markers, refueling depots, and other supporting facilities.

Escape, Evacuation and Rescue

Technologies, processes and models that promote effective escape, evacuation and rescue procedures from an installation located in an Arctic environment may be grouped into this category.

Environmental Protection Technologies

This category includes technology relating to spill prevention and response, as well as emissions and pollution control. Spill prevention and response includes technologies for preventing, containing and responding to oil spills in Arctic conditions. It also includes well control and containment technologies, and those for cleaning-up and dispersing oil in ice. Emissions and pollution control includes technologies for preventing pollution and controlling emissions and noise due to operations in Arctic environment (including support vessels).

4 INDUSTRY CONSULTATION AND SYNTHESIS RESULTS

4.1 Overview

In this chapter a summary of the industry consultation process and synthesized results are presented. The results of the literature review, scenario analysis and the industry consultations were synthesized by compiling a master issue list from all three sources, organizing this list into key R&D themes, and mapping this information to the different categories of technology used throughout phases of the development cycle. The ranking method outlined below was then used to assign priority levels to these issues. A summary of the final results is provided later in the chapter and the top priority issues identified from this process are discussed further in Chapter 5.

4.2 Summary of Industry Consultations

To vet the list of issues and technologies identified from the review and scenario analysis tasks and clearly identify where current industry priorities lie, consultation meetings were held with oil and gas industry representatives from Canada, the United States and Norway. As indicated in the list of companies consulted shown in Table 4-1, individuals from oil and gas companies, regulatory bodies, academia, classification societies and other subject matter experts (e.g. consultants) were engaged in this process.

Table 4-1. Organizations who contributed to the industry consultation process

Company	Country
ExxonMobil	Canada, United States
Suncor	Canada
Husky Energy	Canada
Statoil	Canada, Norway
Chevron	Canada
Shell	United States
ConocoPhillips	Canada, United States
Imperial Oil	Canada
ABS	United States
Memorial University	Canada
CJK Engineering	Canada
AKAC	Canada
Marintek	Norway
NTNU	Norway

The list of research issues and technologies generated from the review and scenario analysis was used as a starting point for these discussions, though interviewees were given an opportunity to add or remove items from this list. Detailed notes were taken during these consultation meetings and subsequently were compiled and distilled to isolate specific priority areas. A copy of these distilled notes was sent back to the attendees for final verification and feedback. This also offered individuals an opportunity to include additional items that may have been missed during the initial discussions. While the full details of these discussions are beyond the scope of the present report, the main results from these sessions are synthesized into the analysis and discussions presented herein.

4.3 Prioritization of Results

A Priority Ranking Number P was developed to establish a priority ranking for each issue. The value for P is estimated using the following formula:

$$P = C\sum_{i=1}^{4} R_i \qquad (1)$$

where: $P =$ Priority Ranking Factor
$C =$ Industry Relevance Factor
$R_i =$ Ranking Factors (four used in total)

A description of these factors is given below.

C : Industry Relevance Factor
This factor was used to reflect the relevance of a particular issue to industry based on how many participants identified this as a priority area and whether or not it was identified as a show-stopper issue. The values used for this factor are:

- 5: Identified by industry as show-stopper issue
- 2: Identified as an important issue by many industry participants
- 1: Identified as a relevant issue by one or more industry participants
- 0.5: Identified from literature review, but not highlighted by industry

R_1 : Range of Applicability

This factor was used to reflect if an issue was of broader industry relevance (i.e. applicable to many different Arctic/sub-Arctic basins), or if it was more site-specific. The values used for this factor are:

- 3: relevant to all basins of interest
- 2: relevant to several basins
- 1: relevant to a small number of basins

R_2 : Expected Impact of R&D

This factor was used to reflect the likelihood of R&D in this area making measureable progress in terms of improving safety, or reducing risk and cost. The values used for this factor are:

- 3: high impact
- 2: moderate impact
- 1: low impact

R_3 : Time to Implementation

This factor was used to reflect the timeframe in which benefits of this R&D will be available to industry. For this project, a higher emphasis is placed on longer term priorities. The values used for this factor are:

- 3: >10 years
- 2: 5-10 years
- 1: < 5 years

R_4 : State of Knowledge

This factor was used to reflect the current state of knowledge and the relative size of the knowledge gap that the R&D will attempt to fill. The values used for this factor are:

- 3: low level of understanding (big knowledge gap)
- 2: moderate level of understanding (moderate gap)
- 1: high level of understanding (small knowledge gap)

4.3.1 Interpretation of Color Codes

For the companion chart to this report entitled "The Arctic Development Roadmap R&D Priority Matrix", a color-coding scheme was used to visually identify the priority ranking of specific issues. The interpretation of each of the color codes is as follows:

- ***Red -*** *High Priority R&D Area:* $P \geq 10$
  Issue is critical and/or stands to result in step changes in technology as a result of medium to long-term R&D; cornerstone issue for an R&D initiative.
- ***Yellow -*** *Moderate Priority R&D Area*: $6 < P < 10$
  Issue would significantly benefit from medium to long-term R&D, but is not a critical issue; should be included in R&D programs, but not at the expense of higher priority issues.
- ***Green*** *- Low Priority R&D Area:* $P \leq 6$
  Issue would benefit from medium to long-term R&D, but operations can proceed with current levels of technology and understanding.

4.4 Results

The prioritized issues identified for the thematic R&D categories described in Section 2.2 were mapped to the categories of development technology described in Section 3.3 to form "The Arctic Development Roadmap R&D Priority Matrix". This information is also presented in tabular form in Appendix B. From these results it is the high priority issues (i.e. red blocks) that are of most interest. These 'red' issues have been grouped into the high priority R&D themes described below.

4.4.1 Environmental Protection

Environmental Protection was identified as being the highest priority area, since offshore activities in the Arctic cannot proceed until regulatory approvals are obtained and outstanding issues are addressed. Emergency scenarios (oil spill prevention and response) are presently of most critical priority, though operational considerations (emissions, pollution, noise and environmental footprint) were identified as also being high priority, particularly the need for greater understanding of the effects of seismic on marine life.

A central topic of discussion with industry was the necessity of ensuring same season well control could be established under all conditions. In the Canadian context, regulatory emphasis is placed on demonstrating same season relief well capability throughout a drilling campaign. A major challenge with this requirement is that it becomes difficult to accommodate the operational drilling and the relief well drilling in a single season. This issue becomes more problematic as operations move into deeper water and more severe ice conditions, which generally correspond with shorter drilling seasons and longer operational and relief well drilling windows. This leads to multi-season drilling campaigns to drill a single well, which is not practical for production scenarios that will require multiple wells to be drilled per season. If alternative same season well control technologies or methods could be developed in consultation with regulatory agencies, this could have major implications on the Arctic exploration and development landscape, particularly for deepwater developments.

Another priority area identified was the development of ice detection and monitoring technologies that can be integrated into the oil spill response process to enable effective ice management in support of emergency response operations. The need for new remote sensing technologies to improve detection capabilities for oil in and under different types of ice was also identified. The need to develop improved tools for modeling oil trajectory and fate prediction was also identified. In addition, the development of subsea protection alternatives to reduce risk from ice impacts and sensor-based methods to assess and monitor the integrity of subsea equipment and pipelines under ice are also needed.

4.4.2 Ice Management

Ice Management (IM) is essential for Arctic operations, as it plays a vital role in enabling the movement of vessels through heavy ice conditions and in reducing the likelihood and severity of ice-structure interactions. While the need for improvements to ice management systems in both operational and design contexts was identified, the most critical IM need identified by industry was in the management of ice to support emergency response. Particular emphasis was placed on the need to conduct ice management field trials to demonstrate the effectiveness of ice management under different operating conditions. For instance, towing success rates and efficiencies need to be quantified to allow IM to be properly factored into design, operational and emergency response planning processes.

Ice forecasting and prediction issues, particularly for tactical ice management during spill response also need to be addressed. Sea ice drift forecasting for periods of up to 3-5 days is also very important for ice management in support of station-keeping. Icebreakers supporting vessels that are station-keeping need to manage multi-year (MY) ice inclusions embedded in first-year (FY) that are on the order of a couple hundred meters in extent. To enable this, the development of high resolution MY ice detection technology that can reliably discriminate between FY and MY ice (including with ice melt) was highlighted by industry as a high priority need. While a number of possible monitoring technologies such as satellites, unmanned-aerial-vehicles (UAV) or other remote sensing technologies could be used, the main technical requirement noted is to provide detection and discrimination accuracies that are equivalent to those currently available through helicopter surveys (which are not practical for the 24/7 support required for IM operations). Other challenges identified include the need for improved detection of icebergs in heavy sea states, adverse weather conditions and in pack ice.

In terms of physical management, issues need to be addressed when dealing with very large icebergs, ice islands and MY ice in both open water and pack ice conditions. The need for improved management strategies for small, thick MY floes embedded in FY ice was also highlighted during the consultation meetings. Given the short open water seasons in many Arctic regions, emphasis was placed on the need for research to improve the capacity of IM to extend operating seasons. Other areas of importance identified included the need for tools to support effective decision-making for complex multi-vessel, multi-input operational environments and logistical models to simulate the whole IM system. The need for tools to assist with the training of personnel for ice management activities was also identified.

4.4.3 Ice Mechanics and Loading

Structures and vessels designed for Arctic operations must have adequate structural strength to allow for safe operations under the most extreme ice loads expected during its operational lifetime. The development of improved design methods based on a more complete understanding of ice failure processes and associated mechanics was identified as a high priority need by industry. While a variety of different ice mechanics issues were identified during the consultations, it was clear that the top priority in this category is to address the need for full-scale ice load data for interactions with multi-year ice and icebergs involving large interaction areas (10-100 m^2). Filling this critical data gap will greatly improve understanding of the nature of local and global pressures expected during full-scale interactions, resulting in significant reductions in uncertainty in design load estimation.

In addition to collecting new data, it was recommended that available full-scale data be re-assessed to improve the understanding and modeling of global, local and dynamic ice loads (including ice-induced vibrations) for both design and operations. For structures in shallow water, the need to further study grounded ice rubble formations and spray ice barriers and their effect on reducing design ice loads was also identified. Another issue identified was the need to further quantify the effects of non-uniformities in ice feature geometry on the mechanics and loads expected during ice-structure interactions. For sloping structures, improved understanding and modeling of loads during interactions involving large multi-year ice ridges was also identified as a priority area for further R&D.

Another area of importance identified by industry was the need to improve understanding and modeling of pack ice pressures and its effects, particularly for ship access, offloading or station-keeping. The development of methods and technologies to mitigate the operational effects of high pack pressures was also identified as a high priority area.

4.4.4 Station-keeping in Ice

To extend the operating season of drill ships and floating platforms, systems must be in place to enable the vessels to maintain station in the presence of ice. If maximum allowable offsets are exceeded, operations must be shut down and the drill string and risers pulled to allow the vessel to move off station. To help maximize up-time and improve vessel station-keeping in ice, research needs were identified in several key areas.

In designing a station-keeping system, the limiting scenario will be the case of a drillship drilling a relief well in response to a blowout, since the vessel will need to remain on station during drilling regardless of ice conditions. In determining limit loads for such scenarios, improved understanding and modeling of ice-loads on floating platforms will be needed. Emphasis was again placed on the need for full-scale ice load data.

Improved modeling of ice loads to use in the design of mooring and Dynamic Positioning (DP) systems was indentified as an area of high priority. While the design of ice-capable DP systems was identified as being beneficial, the most commonly encountered view was that mooring systems will be of much greater interest than DP since mooring systems will be used in the majority of cases where floating platforms are required. Moored vessels operating in ice will need to be able to disconnect under high ice loads. To guide decision-making regarding disconnection, the need for systems to monitor the structural integrity of the platform during operations was identified. Since disconnecting/re-connecting would be a regular activity, the turret systems will need to be robustly designed to allow for reliable, routine operational use under heavy ice loads, not only for use in an emergency disconnect. To streamline reconnection, improved methods for retrieving mooring lines are also needed.

4.4.5 Environmental Characterization

Technology that can rapidly and accurately measure environmental data both for design and real-time operations was identified as a high priority. The need for further characterization of regional ice and metocean conditions to support improved design of bottom-founded and floating structures was also commonly identified, though the geographical regions of interest varied depending on where each company held lease blocks. Similarly, there is a need to gather statistical information and build databases of first-year and multi-year ice thickness, floe size, drift speed, strength, ridge dimensions, and ridge densities within floes.

The need for research to develop forecasting models of long term Arctic ice conditions and to assess the engineering implications of changes in climate on sea ice conditions, permafrost and seasonal freezing processes was highlighted. The development of improved tools and models for operational weather forecasting (with higher reliability), assessing sea ice dynamics in marginal ice zones and for providing improved wave height predictions was recommended.

4.4.6 Offshore Safety and Escape, Evacuation, and Rescue (EER)

To enable safe offshore operations, the need to design and validate performance of ice-capable evacuation systems was identified. In considering EER, survivability must also be considered. Opportunities to improve evacuation craft release, retrieval and personnel transfer methods were discussed and the need for improvements to personal safety equipment was identified. Safe working limits for work above sea need to be established and man-over-board rescue technology needs to be developed for Arctic conditions. Technologies to limit outdoor work time in cold environments need to be developed and requirements for rescue and medical treatment related to offshore activities need to be defined. The development of improved simulation tools and training programs for evacuation methods is needed, as is the development of decision making tools for evacuation scenarios. It was also highlighted that methods are needed to help streamline the development and updating of standards and regulations based on new research and technological developments.

4.4.7 Dredging and Trenching

Dredging and trenching issues were also identified as being of high priority, particularly for companies later in the development cycle where greater consideration is being given to pipeline construction issues. A key issue is the design and development of improved dredging and trenching technologies capable of operation in harsh Arctic metocean, ice and geotechnical conditions. Another major issue is the very high cost associated with dredging and trenching operations. High operational costs makes digging very deep trenches cost prohibitive with current technology and therefore alternative protection methods may be required for these circumstances.

R&D to reduce the cost of operations, reduce the required burial depth or produce better trenches for Arctic pipelines would be beneficial. An improved understanding of iceberg scour patterns, frequencies and loads was identified as one of the main area of research that could help reduce burial depth requirements. The length of time required for dredging/trenching is another area of concern. With limited operational windows in the Arctic a means to dredge/trench efficiently is needed. Shallow water also imposes draft restrictions on dredging/trenching vessel, and since the requirements for pipeline protection is greatest in shallow water, this issue needs to be addressed. In deep Arctic water, economical and efficient means to dredge/trench also need to be developed and proven.

Other dredging and trenching issues include how to deal with sediment resulting from operations and how to lower equipment through various ice conditions. Also of concern is the effect of dredging/trenching sound and sediment emissions on subsea ecosystems and mammals. From an operational perspective, the development of best-practices and operability limits needs to be established for vessels performing dredging and trenching operations. Also, the development of training programs and tools to support trenching/dredging operations and address limited experience base for pipeline trenching in Arctic environments would be advantageous.

4.4.8 Simulation and Training

Throughout the industry consultation meetings the need for simulation and training tools continued to resurface, as did the need to capture Arctic work experience gained during the 1970s and 1980s. The main two areas identified for application of simulation and training technology are in training personnel for escape, evacuation and rescue scenarios, and also for training personnel for oil spill response scenarios. Through simulating these emergency response scenarios under realistic, yet safe and controlled conditions, opportunities to improve processes and performance could be realized. Similar opportunities for this type of technology to improve ice management systems were also identified. Another aspect of training and simulation discussed regularly included the use of such tools to study human performance as a function of Arctic working conditions (prolonged periods of daylight or darkness, etc). Exploring avenues to develop programs to train northern people for particular trades (e.g. ice navigators) that would create employment in the offshore and shipping sectors was also recommended.

4.4.9 Hydrocarbon Export Technologies

During the industry consultations, opportunities for step changes in technology were discussed, and the importance of maintaining an awareness of developments in 'non-Arctic' hydrocarbon technologies that could be adapted to Arctic conditions was highlighted. Recent advances in FLNG were identified as one such technology to consider. In regions such as Labrador, industry is faced with large natural gas deposits, iceberg impact and scouring issues for fixed structures and pipelines, and a limited onshore market. In such cases, the development of a portable, direct export technology such as FLNG could be the potential step change in technology needed to make such a development feasible. While such technologies are in a relatively early stage of development, efforts to develop this concept further will be driven largely by demand from non-Arctic regions, and so significant advancements can be expected regardless of current interest levels in Arctic gas. On this basis, FLNG was identified as an export technology of high priority due to its potential for stranded gas exploitation in Arctic regions.

4.4.10 Arctic Drilling

Drilling is the backbone of the offshore oil and gas industry, and it is the cornerstone activity around which many support activities throughout the exploration and production phases are centered. The economic viability of a project is dependent on drilling a sufficient number of production wells. This is a particular challenge for deepwater, since year-round drilling from drill ships will be required. This is currently not possible. For floating platforms, same season relief well requirements dictate that a separate drilling vessel can be quickly made available in an emergency response scenario. To maximize up-time and ensure safe operations for drilling vessels, the need for technology to assist drilling vessel operators in deciding when disconnection is required was also identified. In regions where fixed production platforms can be used for year-round operations, drilling can be carried out from the platform at adequate drilling rates and the above issues are less critical. In all regions and ice conditions, the extremely high cost of drilling in the Arctic is a major issue and discussions around this topic centered on finding ways to reduce the cost of drilling by extending the drilling season through advances in support technology, and/or decreasing the time required to drill a well through advances in drilling technology. Identifying R&D opportunities to help reduce drilling costs and increase the number of wells that can be drilled in a season was clearly a high priority.

5 CONCLUSIONS

Hydrocarbon development in Arctic regions presents significant challenges. While many issues have been identified in this study, it is evident that concerted efforts in several key R&D areas will present the greatest opportunity for industry-wide impact. As illustrated in Figure 5-1, the high priority issues identified during this project may be organized into three tiers. These tiers represent R&D areas identified by industry as being critical to the development of Arctic resources or with potential to result in step changes in technology, knowledge or methodology.

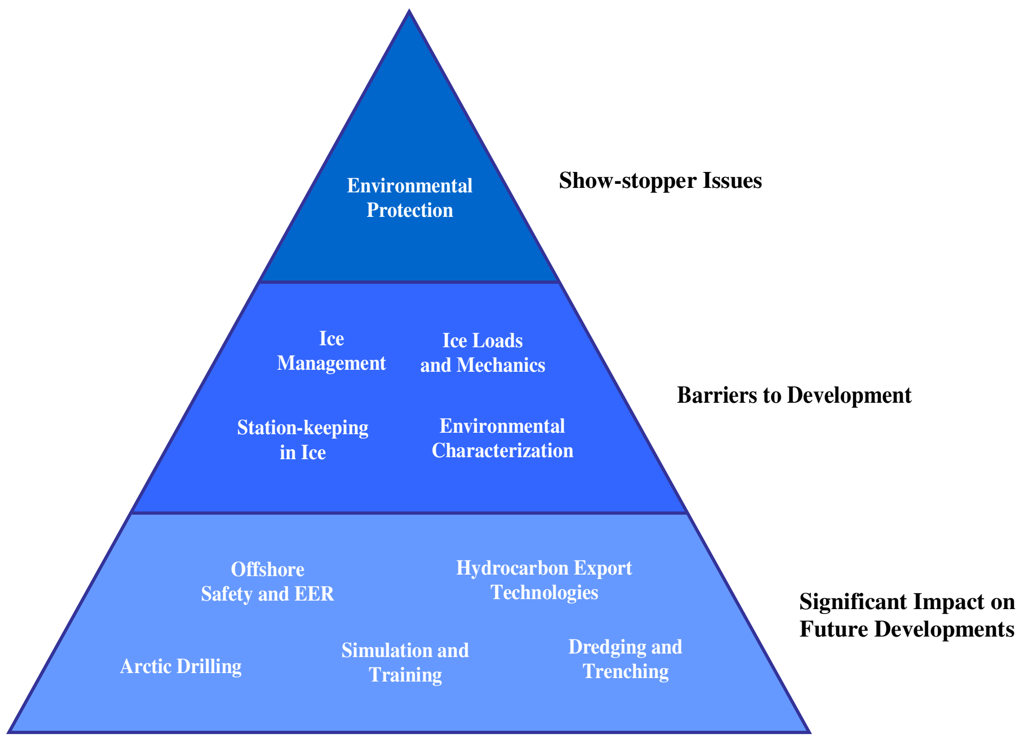


Figure 5-1. Prioritized R&D topics identified from the ADR project

The top tier corresponds to highly important (i.e. show-stopper) issues that must be addressed before Arctic oil and gas development can proceed. The middle tier corresponds to highly important issues where R&D can reduce substantial fundamental gaps and uncertainties that present barriers to development. The bottom tier corresponds to highly important issues for which technological solutions currently exist; further advancement, however, could significantly impact future development projects.

In developing R&D programs around these issues, it is important to maintain an awareness of the multi-dimensional nature of the Arctic development landscape, as was described in Figure 1-2. It for this reason that identified R&D issues have not been treated as being specifically ‘regulatory’ or ‘socio-economic’ issues, but rather they are treated as issues with regulatory, socio-economic and other dimensions which must be simultaneously satisfied.

As discussed in Chapter 1, the high priority R&D issues identified in this project are an important input into the five-year research plan for CARD and serve to highlight priority areas of relevance to the broader research community and various sectors of the oil and gas industry. Through sustained R&D efforts focused on these cornerstone issues, advancements in the knowledge, technology, methodology and training needed to address major issues currently faced by industry will result. These solutions will play a vital role in overcoming existing barriers to development, which will enable the vast hydrocarbon potential of Arctic regions to be realized.

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Appendix A. Summary of Regional Environmental Conditions

A.1 Environmental Conditions - Labrador Shelf (From: ISO 19906:2010(E))

Offshore Labrador has a very harsh environmental climate with heavy pack ice, large icebergs and relatively high wave conditions in the summer months. Sea ice can be quite dynamic with speeds up to 0.4 m/s. In sheltered harbors and bays, shore-fast ice grows to a thickness of about 120 cm during a normal winter. Offshore, level pack ice can reach thicknesses greater than this because of the southward drift of the ice from more northern areas. Ice thicknesses can significantly increase under conditions of pressure. Ice ridge sails of up to 3-5 m high can easily develop under these circumstances (1-2 m is typical). A considerable number of icebergs can be present year-round. Extremely large, tabular icebergs or ice islands (kilometres in length and greater than $20x10^6$ tonnes) can also be present. The sea ice conditions of Labrador are summarized in Table A-1.

Table A-1. Labrador sea ice conditions (From: ISO 19906:2010(E))

Parameter		Average annual value	Range of annual values
Sea ice			
Occurrence	First ice	December	November to January
	Last ice	July	July to August
Level ice (first-year)	Landfast ice thickness, metres	1	0,8 to 1,2
	Floe thickness, metres	1,5	1 to 2
Rafted ice	Rafted ice thickness, metres	4	ND
Rubble fields	Sail height, metres	1,5	ND
	Length, metres	—	ND
Ridges (first-year)	Sail height, metres	2	1 to 5
	Keel depth, metres	8	3 to 15
Level ice (second- and multi-year)	Floe thickness, metres	5	2 to 8
Ridges (second- and multi-year)	Sail height, metres	2	1 to 5
	Keel depth, metres	10	5 to 32
Rubble fields (second- and multi-year)	Average sail height, metres	ND	ND
	Length, metres	ND	ND
Ice movement	Speed in nearshore, metres per second	0,1	0,1 to 0,3
	Speed in offshore, metres per second	0,2	0,2 to 0,4
Icebergs			
Size	Mass, million tonnes	5 to 10 (maximum)	1 to > 20
Frequency	Months present	12	12
	Number per year	1 000	500 to 5 000
	Maximum number per month (number per month)	numerous	ND

The air temperature in this region ranges from approximately 30°C in summer to -40°C in winter, based on coastal sites. Winds can range up to 30 m/s and 40 m/s (1 min average). The average length of the local winter season is from November to April, while the length of the summer season is from June to October. A summary of some of the climate parameters of Labrador is provided in Table A-2.

Table A-2. Labrador temperature and wind conditions (From: ISO 19906:2010(E))

Parameter		Average annual value	Range of annual values
Air temperature	Maximum, degrees Celsius	25	20 to 27
	Minimum, degrees Celsius	–26	–25 to –30
	Freezing degree days	1 600	1 000 to 2 000
Wind speed at 10 m elevation	10 min average, metres per second	30	26 to 38
Wind direction	Dominant winter direction, degrees	300	ND
	Dominant summer direction, degrees	210	ND
Precipitation	Annual rainfall, millimetres	ND	ND
	Annual snowfall, millimetres	ND	ND
Visibility (fog, snow, etc.)	Annual number of days with visibility less than 5 miles	90	ND

Waves in this region have significant heights up to 12.5 m with associated periods of 13 s to 14 s in the offshore region based on hind cast data. Due to the intricacies of the coastline, currents near shore are quite variable. The main Labrador Current has two branches: the cold Baffin Island Current, which is fresher and close to shore, and the West Greenland current. There is a net southerly drift due to the Labrador Current. The main tidal range along the Labrador coast varies from 0.4 m in Lake Melville to 4.6 m at Cape Chidley. The hydrological conditions of Labrador are summarized in Table A-3 below.

Table A-3. Labrador hydrological conditions (From: ISO 19906:2010(E))

Parameter		Average annual value	Range of annual values
Waves, offshore (> 100 m water depth)	Significant wave height annual maximum, metres	11,4	8,2 to 14,0
	Range of zero-crossing periods, seconds	10,4	8,4 to 11,8
Current	Near-surface maximum speed, centimetres per second	20	15 to 40
	Bottom maximum speed, centimetres per second	ND	ND
Tidal current	Maximum surface speed, centimetres per second	ND	ND
Tide	Tidal range (total), metres	ND	ND
Wind-induced surge	Water depth increase range total, metres	ND	ND
Water salinity	Average surface salinity, parts per thousand	ND	ND
Water temperature	Summer surface maximum, degrees Celsius	ND	ND
	Summer surface average, degrees Celsius	5	ND
Seabed geotechnical — Ice-induced gouge	Gouge depth, metres	< 2	ND
	Water depth range, metres	≈ 220	ND
Seismic	Magnitude	ND	ND

A.2 Environmental Conditions – Greenland (From: ISO 19906:2010(E))

The waters of the eastern Davis Strait are normally free from sea ice from April/May until November/December. During the winter and early spring months, sea ice normally covers most of the Davis Strait north of 65 °N, except in areas close to the Greenland coast. In Greenland areas south of 65 °N to 67 °N, sea ice free areas dominate throughout the year. First-year ice is the predominant sea ice type in the Davis Strait and southern Baffin Bay area however; small amounts of multi-year ice of Arctic Ocean origin occasionally drift into the western parts of the area. The sea ice reaches its maximum thickness of about 50 cm to 90 cm in eastern parts (of the Davis Strait) at the end of the freeze-up season in March/April. The western and central parts of Davis Strait are dominated by medium and thick first-year ice categories mixed with small amounts (1/10 to 3/10) of multi-year ice. The ice floe size ranges from large floes about 1 km wide to vast floes larger than 10 km.

The east coast of Greenland is covered by a wide belt of multi-year sea ice which is normally present most of the year. Usually, the multi-year ice reaches the Cape Farewell area in December/January, depending on the intensity of the East Greenland Current and the amount of sea ice in it. The quantity of multi-year ice present in South Greenland waters peaks in early the summer months. The waters near or south of Paamiut are normally free from multi-year sea ice beginning in early August. The size of the multiyear ice floes along the east coast is normally about 5 m to 20 m and has never been recorded above 100 m.

Icebergs can occur everywhere in the waters of west Greenland, though in some areas their presence is rare. The seasonal maximum of icebergs in the southeastern Davis Strait is normally in July and August while the seasonal minimum of icebergs near the Fyllas Banke area is normally during the autumn and early winter months of September to December. The maximum iceberg density off southwest Greenland is expected in early and mid-summer. Most of the icebergs drifting southward from Baffin Bay in the western part of the Davis Strait occur within 100 km to 150 km of the Baffin Island shore. Summaries of the Greenland sea ice and iceberg conditions are provided in Table A-4.

Table A-4. Greenland ice conditions (From: ISO 19906:2010(E))

Parameter		**Average Annual Value**
Sea Ice		
Occurrence	First Ice	January
	Last Ice	May
Level Ice (first-year)	Landfast Ice Thickness (m)	0.3 to 0.7
Multi-Year Ice Flow	Floe Thickness (m)	2 to 3
Icebergs		
Size	Mean Mass (tonnes x 10^6)	0.5 to 1
	Maximum Mass (tonnes x 10^6)	8
	Mean Draught (m)	60 to 80
	Maximum Draught (m)	120 to 130 *
Drift	Mean Direction (to)	NW
Frequency	Months Present	All Year

*depending on water depth

Observations indicate that the largest icebergs are most frequently found in two separate areas: south of 64 °N and north of 66 °N. South of 64 °N, the mass near the 200 m depth contour varies between 1.4×10^6 tonnes and 4.1×10^6 tonnes with a maximum mass of

8.0×10^6 tonnes. The mean draught is 60 m to 80 m and maximum draught is 138 m. North of 66 °N, the largest icebergs are found north and west of Store Hellefiske Banke, where the mean iceberg mass is about 2×10^6 tonnes and maximum mass 15×10^6 tonnes. In Disko Bay, the masses are in the range of 5×10^6 tonnes to 11×10^6 tonnes with a maximum recorded mass of 32×10^6 tonnes. Mean draught is 80 m to 125 m and maximum draught is 187 m. Between the two large iceberg areas (64 °N and 66 °N), masses are between 0.3×10^6 tonnes and 0.7×10^6 tonnes. The maximum mass is 2.8×10^6 tonnes. Mean draught is 50 m to 70 m and maximum draught 125 m.

For all areas of Greenland, the coldest month of the year is February and the warmest month is August. In coastal areas the warmest month of the year is usually July. To the west of Greenland (Baffin Bay and Davis Strait areas) the mean air temperature is below 10 °C year round. To the north, cool summers and very cold winters occur, with a range between the coldest and warmest month of as large as 30 °C. To the south, cool summers and relatively mild winters with ranges of less than 10 °C occur. In the coastal zone, summer temperatures as high as 15 °C or more can occur, even in summer, under certain conditions. Average temperature and wind values, over the entire Greenland region, are provided in Table A-5.

Table A-5. Greenland temperature and wind conditions (From: ISO 19906:2010(E))

Parameter		**Average Annual Value**
Air Temperature	Maximum (^{o}C)	6
	Minimum (^{o}C)	-35
Wind Speed at 10 m elevation	10 min average (m/s)	25
Wind Direction	Dominant (direction / % occurrence)	NNW/14.4

The amount of precipitation is high in the south due to open water and frequent cyclonic activity and low in the north, particularly in winter and spring. The annual amount of precipitation ranges from 20 cm to 30 cm in the mid-western area to more than 100 cm in southernmost Greenland. The majority of the precipitation falls in late summer or in autumn. In winter, precipitation is mostly in the form of snow. Generally, October and June are the rain/snow transition months in the north, while November and May are the transition months in the south. Icing caused by sea spray is frequent from November to April and rare in October and May in open water. Heavy icing sometime occurs in conjunction with persistent, strong northerly and north westerly winds. Strong winds from other directions (particularly southwest) can cause heavy icing as well, though of shorter duration. The Irminger Current flows southward along the east coast of Greenland. A portion of this water continues to travel around the southern tip of Greenland (Cape Farewell), while the other portion remains to circulate within the Irminger Sea. Along the west side of Greenland two current components dominate. Currents include contributions from the Irminger Sea and the North Atlantic. In general, current velocities are weak with values of less than 0.10 m/s. However, in areas close to the coast and also the area just west of the West Greenland Banks the current velocity tends to be larger. In these two areas the current velocities are generally above 0.25 m/s and values of 0.4 m/s to 0.5 m/s are not unusual. A summary of some of the wave, current and water temperature parameters typical of Greenland are provided in Table A-6.

Table A-6. Greenland hydrological data (From: ISO 19906:2010(E))

Parameter		**Average Annual Value**
Waves	Significant Wave Height (m)	7
	Spectral Peak Period (s)	11.9
	Maximum Individual Wave Height (m)	13
	Average Direction of Extreme Waves (from)	SSE
Current	Near-Surface Maximum Speed (cm/s)	100
	Mid-Layer Maximum Speed (cm/s)	45
	Bottom Maximum Speed (cm/s)	30
Water Temperature	Annual Surface Maximum (^{o}C)	7.5
	Summer Surface Average (^{o}C)	3.7
	Annual Bottom Maximum (^{o}C)	4
	Annual Bottom Average (^{o}C)	3.7

The semi-diurnal tide is the most influential tide component on the west coast of Greenland. The greatest tide amplitude along the west coast of Greenland is 120 cm and found in the Nuuk area. This large tidal amplitude decreases to approximately 40 cm north of Disko Island.

A.3 Environmental Conditions – Beaufort Sea (From: ISO 19906:2010(E))

The Beaufort Sea is located north of Alaska, the Northwest Territories and the Yukon and west of the Canadian Arctic Islands. The south-eastern Beaufort Sea floor is comprised of three main bathymetric features. The first is the continental shelf, which slopes gently from the coastline to water depths of approximately 100 m. The second is the continental slope which angles steeply from the edge of this shelf to depths of 1000 m. The third feature is the trench-like Mackenzie Canyon, which transects a portion of the shelf. The two main resource basins in this region, the Arctic Alaska Basin (estimated hydrocarbons in-place of 29,960 MMBO and 221,397 BCFG) and the Amerasia Basin (estimated hydrocarbons in-place of 9,723 MMBO and 56,891 BCFG) have some of the greatest resource potential in the Arctic.

Mapping surveys of the Beaufort Sea have indicated that the seabed is heavily scoured, with a maximum recent gouge depth of 5 m that was measured in 30 m water depth. These seabed scours were created by large first-year and multi-year ice ridges. The spatial frequency of ice gouges varies significantly across the Beaufort seabed. Sonar surveys indicate that the maximum spatial frequency is almost 20 gouges per kilometre per year for water depths of 0 m to 10 m (over a survey route length of 8 km) and is approximately 6 gouges per kilometre per year for water depths of 20 m to 30 m (over a survey route length of 5 km).

The top layer of the Beaufort Sea floor consists largely of marine silts and clays that have been carried to the sea by the Mackenzie River. This upper layer is generally between 0.5 m to 35 m thick and often contain traces of fine sand and organics. Coarse materials such as sands and fine gravels can also be observed. Beneath the upper sea-floor layer is a widespread layer of permafrost. The permafrost layer is typically encountered between 50m and 150 m below the seafloor and can be several hundred meters (or more) in thickness. Permafrost can also be found in fairly close proximity to the seafloor, with ice features often being observed in shallow boreholes. Some other noteworthy features of the Beaufort Sea floor include: multiple hill features (pingo-like), shallow pockets of gas and deep gas hydrate formations. Over 200 of the pingo-like features were identified between the 20 m and the 200 m isobaths and from 128 °W to 136 °W. These features can rise to within 18 m of the sea surface. Some general information relating to the Beaufort Sea location, ice season and water depths are summarized in Table A-7.

Table A-7. Beaufort Sea general information (From: ISO 19906:2010(E))

Area of coverage	69° N to 75 °N, 125° W to 152° W
Length of ice covered season	early October to late July
Length of open water season	August to early October
Range of water depths, metres	2 to 90, to several thousand

The ice conditions in the Beaufort Sea may be categorized into three regions: the Arctic polar pack zone, the seasonal or transitional (shear) zone and the land fast ice zone

The Arctic polar pack is composed of multi-year ice with a level ice thickness up to 5 m and ridges that can be 25 m thick. The polar pack is present year round and circulates with the currents and winds in the Arctic Ocean. On average, the boundary of the Arctic pack lies from near Cape Prince Alfred off Banks Island south-westward to some 200 km north of Herschel Island and then westward some 200 km off the Alaska north coast.

The seasonal transitional zone extends from the edge of the land fast ice to the edge of the polar pack ice. The zone width can vary extensively within a season and from year to year from a few kilometres to over 300 km. This zone is primarily composed of first-year ice however; there can be a large number of multi-year and second-year ice floes as well. The seasonal transitional zone ice is highly dynamic and vast movement can take place throughout the winter with typical movement speeds of 3 km/day to 13 km/day. The moving ice results in deformations in the ice sheet and the creation of both ridges and leads. Ridge sails have been observed to range up to 6 m. If the ridge survives the summer season, it largely desalinates and consolidates to form a multi-year ice ridge. The quantity of ridges increases rapidly in the first part of the winter and remains relatively constant after February.

The land fast ice region is extensive and can form out to a water depth of approximately 20 m. This region is composed primarily of first-year ice. Multi-year ice, if present during the freeze-up period, is frozen into the sheet. The ice begins to grow over the late September to mid-October period and reaches a maximum thickness of approximately 1.9 m in late April. Northwest winds die off in the spring of the year and the east and southeast winds become predominant. The spring east and south-eastern winds induce the formation of a polynya along the edge of the land fast ice. In June, melt begins in the Mackenzie delta and the Amundsen Gulf. An open water area develops quickly in the Mackenzie delta while the land fast ice in the Amundsen Gulf typically fractures in late

June and then ice drifts out and decays. Along the Tuktoyaktuk Peninsula the land fast ice fractures in early July. However, during a cold summer, the land fast ice may not completely break until mid-July.

Extreme ice features of the Beaufort Sea include ice islands and multi-year hummock fields. Ice islands originate from glaciers and have been documented with top area of up to 697 km^2 and thickness of up to 60 m. Ice islands are rare in the Beaufort Sea however, due to their large size they present a potential threat to offshore structures in waters greater than 20 m deep.

Open drift ice conditions along the entire coast line do not develop until the first week of August and an open water route does not develop until the first week of September. The date at which freeze-up occurs in the Beaufort depends to a large extent on the location of the southern limit of the Arctic pack. In general, new ice formation starts among the multi-year floes in late September and spreads both southward and seaward from the coast. By late October much of the ice is at the first-year stage (i.e. > 30 cm thick) out to the Arctic pack. Ice conditions for the Beaufort Sea region are summarized in Table A-8.

The Beaufort Sea is also subject to strong winds which are influenced by the sharp thermal contrast of the land and water to the high coastal lands. Based on environmental observations, it can be expected that once every 50 years winds with an hourly average of 104 km/hr and a 1 minute average of 140 km/hr will occur.

The dominant wind direction ranges from the northeast to southeast during any month of the year. During the summer months southerly winds are rare. From July to September, long periods of easterly winds are common. However, westerly to north-westerly winds that exceed 36 km/hr can become persistent.

In the Beaufort Sea, extreme wind, wave, and surge conditions occur during autumn storms prior to freeze-up. Easterly storms are characterized by strong winds of long duration (usually several days), while westerly storms are associated with extra-tropical cyclones that track from west to east or northwest to southeast across the Beaufort Sea. Westerly storms generally produce higher waves than easterly storms in areas close to shore, where wave heights are limited by breaking. Outside the breaker zone, easterly storms produce somewhat higher waves than westerly storms. Characteristics of the Beaufort Sea climate are summarized in Table A-9.

Table A-8. Beaufort Sea ice conditions (From: ISO 19906:2010(E))

Parameter		Average annual value	Range of annual values
Sea ice			
Occurrence	First ice	October	Late September to late October
	Last ice	July	Early July to mid-August
Level ice (first-year)	Landfast ice thickness, metres	1,8	1,5 to 2,3
	Floe thickness, metres	1,8	1,5 to 2,3
Rafted ice	Rafted ice thickness, metres	3	2,5 to 4,5
Rubble fields	Sail height, metres	5	3 to 6
	Length, metres	100 to 1 000	100 to 1 000
Ridges (first-year)	Sail height, metres	5	3 to 6
	Keel depth, metres	25	15 to 28
Stamukhi	Water depth range, metres	20	15 to 30
	Sail height, metres	5 to 10	up to 20
Level ice (second- and multi-year)	Ice thickness, metres	3 to 6	2 to 11
	Floe thickness, metres	5	2 to 20
Ridges (second- and multi-year)	Sail height, metres	Significant	Significant
	Keel depth, metres	20	10 to 35
Rubble fields (second- and multi-year)	Average sail height, metres	2 to 5	3 to 6
	Length annual maximum, metres	750	50 to 2300
Ice movement	Speed in nearshore, metres per second	0,06	0,04 to 0,2
	Speed in offshore, metres per second	0,08	0,06 to 1,0
Icebergs/ice islands			
Size	Mass, million tonnes	10	ND
Frequency	Months present	Poorly known	Poorly known
	Number per year	Poorly known	Poorly known
	Maximum number per month	Rare	Rare

Table A-9. Beaufort Sea climate parameters (From: ISO 19906:2010(E))

Parameter		Average annual value	Range of annual values
Air temperature	Maximum, degrees Celsius	20	10 to 30
	Minimum, degrees Celsius	–30	–20 to –40
	Freezing degree days	4 500	3 500 to 5 500
Wind speed at 10 m elevation	10 min average, metres per second	24	18 to 32
Wind direction	Dominant winter direction, degrees	95	ND
	Dominant summer direction, degrees	50 (50 % of strong winds are from N and NW)	ND
Precipitation	Annual rainfall, millimetres	150	100 to 200
	Annual snowfall, millimetres	750	600 to 1 100
Visibility (fog, snow, etc.)	Annual number of days with visibility less than 5 miles	20 % of the time	ND

In the offshore Beaufort, the ocean surface flow is dominated by the clockwise circulation of the Beaufort Gyre, which has average flow speeds of 5 cm/s to 10 cm/s. During storms, flow speeds can reach over 100 cm/s at the southern rim of the Gyre over the western Beaufort Sea. Some of the hydrology parameters of the Canadian Beaufort Sea are summarized in Table A-10.

Table A-10. Hydrology parameters of the Beaufort Sea (From: ISO 19906:2010(E))

Parameter		Average annual value	Range of annual values
Waves, offshore (> 100 m water depth)	Significant wave height annual maximum, metres	3,7	1,8 to 8,5
	Range of zero-crossing periods, seconds	6,7	4,5 to 9,8
Current	Near-surface maximum speed, centimetres per second	40	20 to 100
	Bottom maximum speed, centimetres per second	2 to 5	1 to 50
Tidal current	Maximum surface speed, centimetres per second	low	ND
Tide	Tidal range (total), metres	0,3	0,3 to 0,6
Wind-induced surge	Water depth increase range total, metres	1	1 to 4
Water salinity	Average surface salinity, parts per thousand	2 to 30	0 to 33
Water temperature	Summer surface maximum, degrees Celsius	10	2 to 12
	Summer surface average, degrees Celsius	5 to 7	0 to 10
Seabed geotechnical – Ice-induced gouge	Gouge depth, metres	0,6	0,1 to 5
	Water depth range, metres	≈ 30	≈ 50
Seismic	Magnitude	3 to 5	5,5 (in 1937) and 6,5 (in 1920)

Appendix B. Detailed Summary of Prioritized R&D Issues

Table B-1. Detailed summary of prioritized R&D issues (Table 1 of 9)

Issues		Hydrocarbon Detection, Exploration and Evaluation Technology			Ice Management Technology		Environmental Protection Technology	
		Surface Detection and Remote Sensing	Seismic Technology	Drilling and Well Evaluation	Ice Detection and Monitoring Technology	Physical Ice Management	Spill Prevention and Response	Emissions and Pollution Control
1. Environmental Characterization	Ice and Metocean Environment	More complete understanding of characteristics of large ice features; Development of tools capable of monitoring ice conditions.	Development of seismic technology capable of operating in harsh ice and metocean environments.	Accurate, near real-time environmental data needed to support drilling operations.	Technology that can rapidly and accurately measure environmental data both for design and real-time operations would be beneficial; Develop database of first and multi-year ice characteristics.	Understanding the effects of climate change in altering presence and properties of ice to guide development of IM systems; Research and development to improve towing operations in pack ice and in high seas.	Improved understanding of biological environment and effects of dispersants and other spill countermeasures on marine biology; Development of improved environmental forecasting models.	Need improved understanding of biological environment and habits of marine mammals to account for biological cycles and traditional practices; improved environmental forecasting models would be beneficial.
	Bathymetry, Geotechnical, Geophysical and Geospatial Information	Larger, more detailed environmental databases (ice conditions, current data, bathymetry, geotechnical and geological data); Satellite tools for seep mapping for open water and ice conditions.	Improvements to seismic technology to advance the evaluation of frontier basin geology and hydrocarbon potential; Development of 3D visualization tools for reservoir engineering, geology and geophysics.	Development of drilling and well evaluation technologies capable of operation in large water depths and in arctic conditions.	Centralized data management would be beneficial to reduce duplication and increase efficiency.	Knowledge of local bathymetry required to plot successful tow trajectories.	Consideration of basin bathymetry and seabed topography in development of spill response strategies; Determination of the effect of bathymetry on the degree of oil spread.	Detailed seabed mapping to improve routing of ships and pipelines to minimize environmental risk.
2. Ice Structure Interaction	Ice Mechanics and Ice Loading	Improved understanding and modeling of pack ice pressures; Improved technologies for characterization of ice properties (i.e. type, thickness).	Seismic tools to improve characterization and understanding of large ice features (e.g. ice islands, ice shelves, etc.)	Improved understanding of ice loads/failure processes and effects on drilling operations; improved drillship designs to deal with heavy ice and extend operational season.	Additional ice environment data is needed to improve statistics and guide design; Improvements to ice detection technology and drift forecasting models to help reduce uncertainty in ice load estimates.	Full-scale field experiments are needed to collect load data for large interaction areas and enhance understanding of large scale ice failure processes	Design and development of mechanical clean up technology that is efficient for a wide range of ice conditions.	Assessment of ice loads on pollution prevention support vessels.
	Station Keeping in Ice	Improvements in detection technologies to improve tactical ice management and station keeping operations.	Seismic tools to allow evaluation of sea floor geology to guide the determination of effective anchor types and mooring arrangements.	Define limits of existing station-keeping technology; Improvements to station keeping systems to support drilling in managed ice; Development of improved technologies to increase allowable offset distance while drilling.	Improved characterization of ice conditions/loads to guide design of station keeping systems; Ice condition monitoring and drift/ice load modeling needed for IM and DP operations.	The limits of current station-keeping systems need to be defined and the effectiveness of IM in helping vessels keep on station needs to be evaluated.	Station keeping is required for both operations and during emergency response; Need improved understanding of station-keeping ice loads.	Station keeping solutions for vessels supporting emission control and prevention operations.
3. Subsea Issues	Ice-Soil Interaction, Subsea Protection	Improved methods and data for assessment of scour and pipeline burial depths; Improvements in remote sensing technology to identify and characterize deep draft ice features.	Improved tools for seabed mapping to enable improved detection and modeling of iceberg scour processes and loads.	Development of well control solutions capable operating in an ice-scour environments.	Improvements to detection technologies to allow routine checks of subsea equipment in the presence of sea ice.	Develop tools to enable tow route mapping to restrict interactions between ridge keel and subsea facilities during iceberg towing procedures.	Design technology, other than the glory hole, to effectively protect subsea equipment and prevent oil spill.	

Table B-2. Detailed summary of prioritized R&D issues (Table 2 of 9)

Issues		**Hydrocarbon Detection, Exploration and Evaluation Technology**			**Ice Management Technology**		**Environmental Protection Technology**	
		Surface Detection and Remote Sensing	**Seismic Technology**	**Drilling and Well Evaluation**	**Ice Detection and Monitoring Technology**	**Physical Ice Management**	**Spill Prevention and Response**	**Emissions and Pollution Control**
4. Ice Management	**Ice Management**	Detecting MY floes in FY ice (including with ice melt); Long range ice detection technologies are needed for operations.	Develop seismic technologies that can operate in managed ice conditions (with ice management support).	Improved drilling platform design to reduce/eliminate required ice management support.	Development of detection systems with the equivalent efficacy of helicopter surveys; Iceberg detection in heavy sea states, adverse weather conditions and in pack ice.	Physical management for very large icebergs, ice islands and MY ice in heavy sea states/pack ice; Improved strategies for small, thick MY floes; Demonstration of effectiveness of IM systems .	Ice forecasting and prediction issues, particularly for tactical ice management during spill response.	Emissions associated with IM vessels need to be considered to ensure adequate ship power is available to manage ice, while satisfying emissions control requirements.
5. Environmental Protection	**Environmental Protection**	Technology for detection of oil in/under different types of ice; Oil trajectory forecasting and fate prediction models.	The effects of seismic on marine life needs to be more completely understood..	Development of contingency plan for disposal of drilling mud and other drilling waste in remote areas.	Integration of ice detection and monitoring technology into oil spill response; Detection of oil under ice.	Technologies and training programs for IM during spill response in ice are needed; Towing practices to reduce carbon footprint are needed;	Same season well control (relief well) is a key issues; Getting regulatory approval to used alternatives to relief wells is needed, particularly for deepwater areas.	R&D to support direct-injection dispersant use is needed; Minimization of footprint is required; Need to demonstrate waste fluid re-injection can be done safely.
6. Engineering and Design	**Engineering and Design Issues**	Improvements to remote sensing devices to allow gathering data for models of wave-ice interaction , wave propagation and wave attenuation in ice for design.	Improvements in technology to allow gathering of detailed seabed information required for foundation design.	Development of drilling and well evaluation tools capable of operation in harsh arctic environments (e.g. drill bits capable of cutting through permafrost).	Improvements to detection and monitoring technologies to allow better assessment of environmental conditions used in design.	Define bollard pull requirements to tow large icebergs; Design of towing equipment that capable of towing large icebergs (>1 million tonnes).	Design and development of response measures for Arctic use late in operational season; Ensuring regulatory compliance is essential.	Design of technology to detect gas leak and limit emissions; Improved engine efficiency and emissions control technologies needed for platforms and support vessels in the Arctic.
7. Hydrocarbon Export	**Issues for Pipelines, Tankers, and Hydrocarbon Export Alternatives**	Improvements in remote sensing technologies to allow monitoring of arctic pipelines; real-time ice detection and monitoring needed to support export operations.	Improved seabed mapping for pipeline and shipping route optimization, as well as scour rates and depths for pipeline burial depth calculations.	Explore use of horizontal/extended reach drilling for installation of pipelines.	Improve iceberg profiling technology (e.g. AUV) to monitor pipeline risk; Improve surveillance, tracking, forecasting and mitigation of sea ice and icebergs near installations to minimize risk during offloading operations.	Develop physical management strategies required during offloading or to support other export activities.	Understanding/minimizing the environmental risk and effects of export activities is needed (i.e. minimize environmental footprint).	

Table B-3. Detailed summary of prioritized R&D issues (Table 3 of 9)

Issues		Hydrocarbon Detection, Exploration and Evaluation Technology			Ice Management Technology		Environmental Protection Technology	
		Surface Detection and Remote Sensing	Seismic Technology	Drilling and Well Evaluation	Ice Detection and Monitoring Technology	Physical Ice Management	Spill Prevention and Response	Emissions and Pollution Control
8. Offshore Safety and Human Factors	Offshore Health and Safety Issues	Use of earth observation technology to provide tactical support for EER operations; improve communications links for high latitudes.	Detailed bathymetry information required for evaluation of evacuation options and routes.	Consideration of effects of noise and vibrations resulting from arctic drilling on environment and offshore workers.	Improvements in detection technology to allow advanced warning of possible extreme ice features requiring evacuation and shut-into reduce risk to offshore workers.	Development of technology to automate tow line deployment / recovery methods to reduce risk to personnel on back deck, particularly during heavy sea states.	Research into potential hazards associated with oil burning (as a clean up measure) to ensure best practices are used and ensure safety of offshore workers.	
	Human Factors	Use satellite technology for monitoring individual safety during field operations; improve communications links for high latitudes.	Socio economic issues regarding impact of seismic technology on traditional lifestyles (hunting, fishing, etc.).	Consideration of effects outdoor arctic drilling operations on offshore workers; Development of simulation training programs specific to arctic drilling operations.	Development of tactical ice management tools for monitoring ice conditions, improvement of ice drift forecasting and assisting in decision making processes.	Develop simulation and training for personnel involved with IM operations.	Stakeholders need to be engaged to regarding response technology; Simulation, training, and methods to pass along knowledge and ensure performance during oil spill response are needed.	Development of clean up technologies that limit human exposure (i.e. automated, or remotely operated) are needed.
9. Logistics, Infrastructure and Support	Logistics, Infrastructure and Support Issues	Remote sensing tools to monitor damage to infrastructure and roadways due to permafrost and seasonal freezing; Improved communications and GPS technology needed for high latitude operations.	Improved methodology to improve and streamline time for regulatory approval for seismic use; Detailed bathymetry is required when selecting vessels operate in a particular region (e.g. to avoid grounding)	The sensitivity of drilling operations to logistical and infrastructure issues needs to be better understood and strategies developed to mitigate these effects.	Satellite coverage insufficient for tactical monitoring in some regions.	The sensitivity of IM to logistical/infrastructure issues needs to better understood and strategies developed to mitigate these effects; Methods to assess IM reliability.	The sensitivity of spill response to logistical and infrastructure issues needs to better understood and strategies developed to mitigate these effects; Improved infrastructure to aid in the prevention of pollution and aid in emergency response situations is needed.	
10. Drilling and Operations	Drilling, Completion and Intervention Issues	Improvement to satellite and remote sensing technologies to provide tactical (real-time) support to drilling operations.	Rapid gathering and processing of seismic data are needed to maximize same season operations.	Determine methods to reduce drilling time in arctic areas; Staggered drilling plans are required; Drilling operations are very costly; Issues associated with well control/relief well must be addressed.	Development of real-time detection and monitoring technologies to provide tactical ice management support during drilling and operations to maximize up-time.	Research into improved IM methods to extend operating seasons needed; Develop decision-making criteria for drilling vessels operating in ice environments to allow adequate response time to iceberg threats.	Research into improvements for drilling technology to reduce drilling risks are needed (i.e. alternate well-kill system; spill containment systems).	Development of drilling, completion and intervention plans to decrease the potential of hazardous situation; Development of zero discharge well test.
	Operational Issues (Asset Integrity, Flow Assurance, and Process Related)	Remote monitoring of asset integrity and changes to the environment (e.g. melting permafrost) which can result in damage to equipment or affect inspection and maintenance schedules.	Winterization of seismic technology is needed to ensure reliable operations in Arctic conditions.	Method to assess structural integrity while operating would be beneficial in extending drilling season; Methods for inspection of subsea equipment in areas with sea ice need to be developed.	Developments to allow the use of remote detection technology to monitor asset integrity.	Method to assess structural integrity of platforms or vessels in managed or unmanaged ice while operating would be beneficial in extending drilling season.	Development of routing inspection plans and methods for subsea pipes and well equipment; Research into automated methods of subsea equipment inspection and repair.	Development of clear guidelines for routine inspection of offshore installations specific to Arctic operations.

Table B-4. Detailed summary of prioritized R&D issues (Table 4 of 9)

Issues		Platform Technology: Bottom-founded Structures				Platform Technology: Floating Structures			
		Man-made Islands	Barge/Vessel	GBS	Jacket/Monopod/Jack-up Rig	FPSO	Semi-submersibles	Tension Leg Platform (TLP)	SPAR
1. Environmental Characterization	Ice and Metocean Environment	R&D related to the ice and metocean environment that would improve the design of bottom founded and floating structures for offshore arctic petroleum operations;Database of first-year ice thickness distribution and ridge dimensions; Database of multi-year ice thickness distribution, ridge dimensions, frequency within a floe, floe size distribution and floe speed distribution; Assessment of the engineering implications of climate change on sea ice conditions, permafrost and seasonal freezing processes; Assessment of sea ice dynamics in marginal ice zone; Development of improved weather forecasting models that have a higher reliability; Development of improved wave height prediction tools; Research into long term arctic ice condition forecasting; Improved sea ice statistics (environmental characterization); Research to help define the basic characteristics (thickness, horizontal extent, through ice strength, etc.) and occurrence statistics of extreme ice features (e.g. MY hummock fields).							
	Bathymetry, Geotechnical, Geophysical and Geospatial Information	Development of models to accurately model basin geology and geophysics in arctic environments - this information is needed to guide bottom founded structure design; R&D to extend bathymetric limit imposed on bottom founded structures (in terms of feasibility) to enable bottom founded structures to be used in deeper arctic waters.				Accurate data and models of geotechnical conditions are needed to guide mooring system design; Development of ice capable station-keeping systems capable of operation in a range of water depths are needed.			
2. Ice Structure Interaction	Ice Mechanics and Ice Loading	Improved understanding and modeling of global, local and dynamic ice loads are needed for design and operations; Re-assessment of available data for validation of design loads; Experiments to obtain full-scale ice load data for interactions with multi-year/glacial ice features (areas 10-100m2) are needed; Improved understanding of grounded ice rubble formations and spray ice barriers and their effect on reducing design ice loads is needed; Effects of non-uniform extreme ice feature geometries on loads is needed; Need improved understanding of dynamic ice loads and ice-induced vibrations; Need improved understanding of pack ice pressure effects (particularly for ship access, offloading or station keeping); Improved modeling of ice drift needed; Quantification of adfreeze effect on sloping structures; Improved ice load models are needed for sloping structures; Improved understanding and modeling of physical processes is needed; Improved probabilistic ice load models are needed.							
	Station Keeping in Ice	Station-keeping issues for vessels required to support production and export operations need to addressed.				Improved floater designs are needed for extended operational season; Quick disconnect and re-connect systems for floating platforms under heavy ice loads are needed for regular operations, not only emergency response; Station-keeping tests to validate successful Arctic operation; Design of ice-capable DP systems; Full-scale ice load data; models of ice loads for mooring and DP systems; Method to assess structural integrity of platform while operating would be beneficial to reduce down time and guide decision-making regarding disconnection; Methods for improved retrieval of mooring lines are needed.			
3. Subsea Issues	Ice-Soil Interaction, Subsea Protection	R&D needed to assist the design of subsea tie-ins and other equipment required for production; Increased understanding of gouge process needed; Assess effects of sediment type on scour degradation and estimates of scour frequency; Investigate the relationship between the geotechnical properties of the soil and the scour dimensions; Research to guide accurate estimation of keel shape and gouge shape.							

Table B-5. Detailed summary of prioritized R&D issues (Table 5 of 9)

Issues		Platform Technology: Bottom-founded Structures				Platform Technology: Floating Structures			
		Man-made Islands	Barge/Vessel	GBS	Jacket/Monopod/ Jack-up Rig	FPSO	Semi-submersibles	Tension Leg Platform (TLP)	SPAR
4. Ice Management	Ice Management	Field trials to demonstrate quantify ice management efficiency to allow for inclusion of IM in design process; Development of a tools to assist with Ice Management training; Data management and integrated IM systems are needed to manage the complex multi-vessel, multi-input decision-making environment.							
5. Environmental Protection	Environmental Protection	Construction and installation techniques used for bottom founded structures used need to minimize environmental footprint (e.g. dredging to construct berms or artificial islands);				Construction and installation techniques used for anchor and mooring systems and subsea equipment need to minimize environmental footprint.			
6. Engineering and Design	Engineering and Design Issues	Knowledge of platform structural behavior needed, especially for conditions close to structural limits; Foundation and permafrost issues need to be addressed; Further understanding of ice induced vibrations needed; Investigate loading on multi-leg structure in thick ice conditions to determine if legs respond individually or as a group; R&D to determine if bottom founded structure could be designed for MY ice in > 100 m water depth; Improved understanding of performance of conical structures in multi-year ice needed.				Development of new floating structure concepts capable of drilling and production in Arctic conditions is needed; Dynamic ice loading effects need to be better understood for floaters; Development of effective and efficient disconnect/re-connect systems needed for deepwater Arctic.			
7. Hydrocarbon Export	Issues for Pipelines, Tankers, and Hydrocarbon Export Alternatives	Research to ensure flow assurance in arctic pipelines and offloading to tankers is needed (e.g. limiting hydrate formation with extended distances in cold temperatures); Portable export systems to enable marginal field development are needed (e.g. can be retrofitted/moved to another field).							

Table B-6. Detailed summary of prioritized R&D issues (Table 6 of 9)

Issues		Platform Technology: Bottom-founded Structures				Platform Technology: Floating Structures			
		Man-made Islands	Barge/Vessel	GBS	Jacket/Mono-pod/Jack-up Rig	FPSO	Semi-submersibles	Tension Leg Platform (TLP)	SPAR
8. Offshore Safety and Human Factors	Offshore Health and Safety Issues	Development of methods to improve evacuation of platforms and other installations are needed; Development of improved training programs for evacuation methods are needed; Safe working limits for work above sea need to be established; Man-over-board rescue technology needs to be developed for Arctic environment; Practice to limit outdoor work time in cold environments need to be established; Requirements for rescue and medical treatment related to offshore activities need to be defined.							
	Human Factors	Quantification of effects of arctic conditions on performance and safety of personnel working on arctic platforms is needed; Man-over-board systems are needed for rescue of personnel; Improved systems to allow for simulation-based training of personnel for different emergency response scenarios is needed; Consequences of extreme temperatures, weather and extended periods of light/darkness on offshore workers needs to be better understood; Human performance issues related to impairment of judgment, decision-making, and completion of complex mental and physical tasks, work efficiency and risk of accidents due to fatigue or work environment risks (e.g. snow and ice on work surfaces, overhead, etc.) .							
9. Logistics, Infrastructure and Support	Logistics, Infrastructure and Support Issues	Establish maritime traffic control centre for field and non-field related maritime traffic; R&D to reduce logistical issues relating to construction and installation of bottom founded structures is needed; Improved scheduling an logistics tools are needed to maximize operations during open water season to reduce exposure and risk to personnel; Development of IM fleet simulators to assist in fleet management would be beneficial; Difficulties in communications associated with inadequate satellite coverage, insufficient IT infrastructure and issues with magnetic conditions at high latitudes need to be addressed.				Establish maritime traffic control centre for field and non-field related maritime traffic; R&D to reduce logistical issues relating to disconnection/re-connection of floating structures is needed; Improved scheduling an logistics tools are needed to maximize operations during open water season to reduce exposure and risk to personnel; Development of IM fleet simulators to assist in fleet management would be beneficial; Difficulties in communications associated with inadequate satellite coverage, insufficient IT infrastructure and issues with magnetic conditions at high latitudes need to be addressed.			
10. Drilling and Operations	Drilling, Completion and Intervention Issues	Development of technology to allow riserless drilling and extended reach drilling in the Arctic needed; Development of umbilicals suitable for cold climates is needed; Technologies such as pilot-hole to pilot-hole HDD installations for arctic developments need further development; Research to identify and address issues with pipe-in-pipe operations is needed; Research into the extent of actions from subsea permafrost (frost heave and thaw settlement).				Station-keeping while drilling is required for safe operations, particularly for limiting case of emergency response scenario (i.e. relief well drilling) where need to remain on station for entire time under all possible ice conditions.			
	Operational Issues (Asset Integrity, Flow Assurance, and Process Related)	Method to assess structural integrity of platform while operating would be beneficial to reduce down time; Winterization of installations to allow for safe arctic operation is needed; Research into cathodic protection systems to use in arctic environments; Research to determine the suitability of structural materials and weld materials to environmental conditions to ensure asset integrity (i.e. cold temperatures); Development of heating systems capable of emitting adequate heat to allow for good hydrocarbon flow from facility; R&D into optimal insulation of storage compartments and piping arrangement to promote flow assurance.							

Table B-7. Detailed summary of prioritized R&D issues (Table 7 of 9)

Issues		Subsea Technology		Hydrocarbon Export Technology		Transportation and Support Technology		Escape, Evacuation and Rescue
		Subsea Production and Protection Equipment	**Dredging and Trenching**	**Pipelines**	**Tankers and Gas Export Alternatives**	**Icebreakers and Support Vessels**	**Ports and Infrastructure**	**EER Technologies**
1. Environmental Characterization	**Ice and Metocean Environment**	Improved characterization of iceberg and ridge densities to improve prediction of scour rates and impact frequencies for subsea structures. Development of protective equipment suitable for all ice conditions.	Determination of methods to lower equipment through different types of ice cover and methods to power subsea equipment under ice cover.	Research into insulation of pipelines suitable for harsh metocean environments.	Regional operational seasons need to be defined; Knowledge of ice ridge fields and ice pressures along ship transit routes and their influence on transit time are needed.		Mapping of seasonal accessibility to available infrastructure and transportation routes (e.g. ice roads) in Arctic regions is needed.	Design and develop evacuation technology which can operate successfully in brash ice conditions of concentration larger than 7/10ths.
1. Environmental Characterization	**Bathymetry, Geotechnical, Geophysical and Geospatial Information**	Design of subsea production equipment capable of high reliability operation in deepwater Arctic environment; Development of a regional gouge database.	R&D into new techniques and technologies that can operate in different soil and rock conditions are needed; Regional bathymetric and geotechnical data is needed to optimize routing to minimize dredging/trenching depths and cost.	Research into improved modeling of seabed to allow accurate (and less conservative) prediction of required pipeline burial depths.	The age and quality of nautical chart data (with some data still shown from the 1800's) need to be assessed and updated to reduce risk of groundings and ensure safe vessel operations.		Updated navigational charts, bathymetric information, and geotechnical information is needed to support development of improved Arctic infrastructure.	Site-specific bathymetric and geospatial information need to be considered when designing evacuation options for a particular installation.
2. Ice Structure Interaction	**Ice Mechanics and Ice Loading**	Assessment of iceberg keel loads and risk of impact on subsea equipment; Define load requirements for subsea protection structures.	Increased knowledge regarding allowable interaction of ice features with tow cables and umbilicals required for trenching operations.	Design of pipeline, including material selection, to withstand ice induced loads at sub-zero temperatures.	Guidance on improved operational performance in high pack pressures is needed; Improved understanding and methods for estimating ice loads for design are needed.	Improved designs to deal with heavy ice and extend operational season are needed; Research to enhance the fatigue life of materials used to construct icebreakers and support vessels.	Assessment of ice loads for the design of ports and supply terminals is important; Design of navigational aides capable of withstanding heavy ice conditions is needed.	Determination of maximum ice loading a conventional evacuation craft can withstand and limiting ice conditions in which craft is operational.
2. Ice Structure Interaction	**Station Keeping in Ice**	Best practices and operability limits for installation of subsea equipment and protection structures from vessels station-keeping in ice need to be established.	Best-practices and operability limits need to be established for support vessels required to keep on station during dredging and trenching operations.	Procedures need to be established for vessels required to station-keep during pipeline installation and maintenance.	Improved DP system design to allow for effective station-keeping during loading and offloading situations.	Improved understanding of station-keeping ice loads are needed; Best practices for effective icebreaking to support vessels trying to maintain station need to be established.	Design of ice-capable station-keeping options for offshore support facilities (i.e. re-fueling buoys).	Station keeping is required for both operations and during emergency response; Need improved understanding of station-keeping ice loads.
3. Subsea Issues	**Ice-Soil Interaction, Subsea Protection**	Development of methods and technologies to protect seafloor facilities and pipelines from ice keels; Improved understanding of ice keel failure strength is needed.	Improved dredging/trenching technologies are needed for burying subsea pipelines; R&D to improve understanding scour and reduce required burial depth is needed.	Improve understanding and modeling of maximum gouge depth and associated loads on pipeline based on ice strength and driving forces; Reduction of pipeline burial depths.	Protection of subsea equipment and offloading terminals from ice is needed.	Improved methods for using support vessels to manage deep draft ice features to reduce scour risk to subsea equipment and infrastructure is needed.	Potential risk of iceberg scour to subsea components of offshore/marine infrastructure needs to be considered.	Improve understanding of Influence of grounded ice features and rubble on deployment of evacuation craft and access by response vessels.

Table B-8. Detailed summary of prioritized R&D issues (Table 8 of 9)

Issues		Subsea Technology		Hydrocarbon Export Technology		Transportation and Support Technology		Escape, Evacuation and Rescue
		Subsea Production and Protection Equipment	Dredging and Trenching	Pipelines	Tankers and Gas Export Alternatives	Icebreakers and Support Vessels	Ports and Infrastructure	EER Technologies
4. Ice Management	Ice Management	Improved understanding of risks associated with deep draft ice features and define role of IM in reducing risk to subsea facilities; Improve AUV/ROV for surveying and monitoring under ice and in managed ice conditions.	Methods to establish the effectiveness of IM in reducing risks to subsea facilities to reduce glory hole and burial requirements; IM to support dredging/trenching in ice environments needs further work.	Improved methods to allow installation of pipelines with ice management support to extend construction and installation window.	Considerations of ice management operations while offloading from Arctic terminals; Establish best-practices for operating convoy of a small beam icebreaker and a large beam cargo/tanker vessel.	Icebreaking patterns and strategies need to be better understood to optimize IM efficiency; multi-function icebreaking vessels are needed.	Icebreaker support to allow access to port facilities and other infrastructure will be needed.	Consideration of available ice management vessels within EER plans to help facilitate rescue procedures.
5. Environmental Protection	Environmental Protection	Same season well control (relief well) issues must be addressed; capping and containment technologies need to be developed for the Arctic; Subsea protection alternatives to reduce risk from ice impacts are needed.	Effects of underwater sound on mammals and mitigation of sound emissions needs to be considered.	Methods to assess and monitor integrity of subsea equipment and pipelines under ice are required; Development of sensor based leak detection systems to limit hazard of a major oil spill are needed.	Develop preventative measures for oil spills from tanker systems; Development of fuel efficient tankers.	Design of ice capable spill containment ships/systems is needed; Operational roles of icebreaking vessels during emergency response scenarios needs to be more clearly defined.	Mapping the limits of current response measures and infrastructure would be beneficial to highlight where improvements are needed.	Consideration of effects of offshore hazard situations in development of evacuation, escape and rescue plans (e.g. how smoke from a fire would affect platform evacuation).
6. Engineering and Design	Engineering and Design Issues	Subsea protection alternatives need to be designed; Technology to facilitate unmanned subsea operations (i.e.. power supply systems) needed; Ice capable ROV retrieval system needed.	Modification of existing trenching equipment to allow operation in greater water depths in Arctic conditions; There are no existing technologies that satisfies all Arctic trenching functional requirements.	Improved pipeline design methods to avail of plastic reserve capacity in ductile steels are needed; Design pipelines capable of withstanding forces from frost heave and thaw settlement processes.	Design of offloading systems for ice conditions; Feasibility of double-acting tankers for high Arctic needs further exploration; Large cargo ships with improved maneuverability are needed.	Winterization of systems and support equipment for personnel will be needed; Assessment and Integration of work done to date on vessel design, materials, corrosion and ice loads on machinery are needed.	Permafrost degradation issues are an important consideration in the design of onshore buildings and infrastructure.	Winterization of systems and equipment for personnel will be needed; Design and develop deployment and retrieval concept along with evacuation craft (e.g. hovercraft) that is operable in regions with harsh ice conditions.
7. Hydrocarbon Export	Issues for Pipelines, Tankers, and Hydrocarbon Export Alternatives	Development of feasible protective alternatives for subsea equipment and pipelines are required; Geohazards, subsea slope stability and seismic activity need to be considered when evaluating export alternatives.	Pipe laying, trenching and burial depth issues need to be addressed; Rapid escalation of cost as a function of increasing burial depth needs to be addressed.	Issues with bringing an Arctic pipeline to shore (landfalls) need to be addressed.	Improved understanding of the capabilities of Arctic FLNG technology to impact long-term development of stranded gas in Arctic regions is needed.	Optimize tanker designs and shipping routes to minimize requirements for escort icebreakers during export.	There are currently a limited number of arctic navigation aids; Development of additional navigation aids along main shipping routes is needed.	Export vessels and facilities must be accounted for in overall EER planning process.

Table B-9. Detailed summary of prioritized R&D issues (Table 9 of 9)

Issues		Subsea Technology		Hydrocarbon Export Technology		Transportation and Support Technology		Escape, Evacuation and Rescue
		Subsea Production and Protection Equipment	Dredging and Trenching	Pipelines	Tankers and Gas Export Alternatives	Icebreakers and Support Vessels	Ports and Infrastructure	EER Technologies
8. Offshore Safety and Human Factors	Offshore Health and Safety Issues	Development of subsea drilling, robotics and automation of processes for Arctic operations to limit human exposure to Arctic environments.	Development of training programs and tools to support trenching/dredging operations and address limited experience base for pipeline trenching in Arctic environments.	Automated systems for detection of pipeline leaks are needed to minimize exposure of personnel required to conduct inspections and servicing.	Risks due to possible collisions, groundings, or other accidents need to be evaluated and routes optimized to minimize risk to personnel and the environment.	Ice-capable ships are needed for emergency response to allow for safe evacuation and rescue in ice conditions; Impact of icebreaking on traditional transportation routes used by northern people must be considered.	SAR infrastructure is very sparse in the Arctic, which makes challenges due to remoteness, large distances and harsh conditions more challenging; Navigational aids are needed along transportation/shipping routes to reduce risk.	Design of ice-capable evacuation system; Evacuation craft release, retrieval and personnel transfer methods; Improvements to personal safety equipment.
	Human Factors	Development of training programs for ROVs in Arctic conditions and remote operation of subsea equipment. Improved tools to support decision making for use of IM for protection of subsea facilities.	Development of technology to reduce exposure of personnel to harsh/cold conditions during trenching dredging operations.	Development of procedures and technologies to limit exposure for personnel to elements during pipeline installation and maintenance operations.	Training programs for ice navigators and training of northern people to work on Arctic tankers and vessels would be beneficial.	Simulation, training, and methods to pass along knowledge are needed; programs to train local people (e.g. ice navigators) would be beneficial; quantification of effects of human factors on performance is important.	Training of staff required to maintain and operate northern ports and infrastructure is required.	Development of decision making algorithms for evacuation scenarios; methods to efficiently develop and update standards and regulations based on new research and technology developments; Simulation and training for evacuation scenarios is needed .
9. Logistics, Infrastructure and Support	Logistics, Infrastructure and Support Issues	Logistical challenges associated with provision of vessels required for the installation and servicing of subsea equipment and protection structures.	R&D to improved processes for dredging/trenching in environments with ice to minimize required support vessels and ensure reliability to maximize uptime during operations in remote regions.	Research to determine effective insulation for Arctic pipelines that allows heat gain during installation and prevents dramatic heat loss when installed to prevent issues with flow rate.	Improved understanding of issues and operational guidance for selection of optimal tanker/shipping routes and addressing of transportation issues is needed.	Tools such as logistics simulators are needed to assist with management of icebreaker fleet to maximize effectiveness of overall IM system. .	Lack of Arctic infrastructure is a major challenge; Development of offshore supply base needs further consideration as possible option for some regions.	The sensitivity of emergency response to logistical and infrastructure issues needs to better understood and strategies developed to mitigate these effects;
10. Drilling and Operations	Drilling, Completion and Intervention Issues	Development of automated/subsea drilling technology with riserless mud recovery system; Ensuring well integrity is required; subsea risks due to gas hydrates need to be better understood.	Further work needed on Well Intersection Method (WIM) for Arctic environments to assess economics in comparison to trenched pipeline method; Research into methods for dealing with risks from shallow gas is needed.	Research to prevent the formation of gas hydrates in Arctic pipelines and alleviate this issue (e.g. adequate heating systems).	Assess the temperature influence of oil flow rate. Methods to prevent formation of gas hydrates in flowlines are needed.	Multi-purpose icebreaking support vessels are required to support drilling operations, and well completion and intervention activities.	All supplies and equipment to support exploration drilling must be brought in with the drill ship; Supply terminals will be needed to store supplies required for year-round operations as projects move towards production drilling	Drilling vessels must be equipped to deal with other potential hazards to (e.g. H2S, blowouts, fires, explosions, shallow gas) while ensuring safe EER for personnel during such scenarios.
	Operational Issues (Asset Integrity, Flow Assurance, and Process Related)	Inspection and servicing of subsea equipment in areas with sea ice is required; Design of under-ice robotics to conduct routine maintenance. Methods to assess and monitor integrity of subsea assets is needed.	Method of dealing with possible increase in gas hydrates in the shallow soils of arctic areas, especially in deep water; Development of maintenance and winterization requirements for trenching equipment is needed.	Technologies to prevent hydrate formation and facilitate "cold flow" in subsea pipelines are needed; Pipeline must allow heat gain during installation, while preventing heat loss to aid in free-flow of oil during operations.	Improved technologies for wet gas monitoring are needed; Research involving tanker transit routes and associated risk (based on world experience) is needed;	Method to assess structural integrity while operating would be beneficial in helping extend operational boundaries and extending drilling season.	Reliability of power supply at remote stations (such as remote gate valves on pipelines) need to be ensured; Adequate infrastructure is required to ensure stable power supply for all Arctic operations.	Consider optimal placement of evacuation craft on platform to reduce effects of environmental conditions (e.g. ice or snow) on accessibility and effectiveness of system.

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