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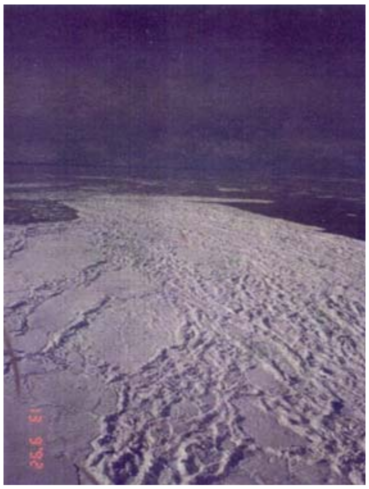



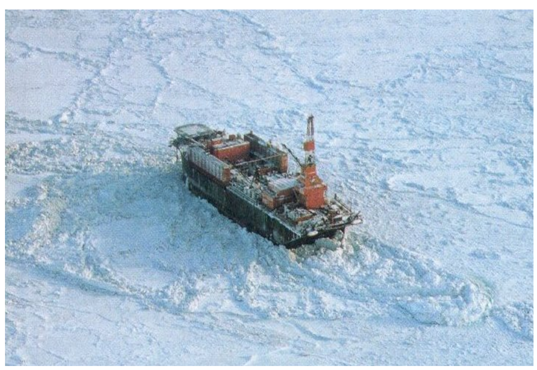


submitted to NRC-CHC
Ottawa, Ontario

PERD/CHC Report 35-60

by

B. Wright & Associates Ltd.

September, 2005

Executive Summary

This report presents the results of an assessment of ice-related R&D requirements for Beaufort Sea production systems. It has been prompted by a general renewal of interest in the opportunities that may become available for Beaufort oil and gas development projects in the future. As part of this work, key ice-related issues that arose during previous exploration activities in the Beaufort Sea are identified, along with the ice-related R&D needs developed in earlier studies. Discussions with representatives from industry, government and expertise groups have also been held as part of this work, to get their views on current ice-related uncertainties and challenges for potential Beaufort Sea developments.

The key ice-related R&D needs that have been identified in this assessment fall into the following topic areas:

- Design ice loads on fixed structures, including:
    - global loads from extreme multi-year ice feature interactions
    - grounded ice rubble formations & their effect on reducing design ice load levels
- Vessel station-keeping in ice (e.g.: tanker loading) & related ice management aspects
- Ice scour and its influence on the design of seafloor facilities
- The engineering implications of climate change on Beaufort Sea ice conditions
- Improved oil spill countermeasures and clean-up methods in ice
- Improved EER methods for platforms operating in ice-covered waters

Other important messages received as part of this R&D requirements assessment include:

- a recognition that many of these ice issues are generic, and also of interest for offshore projects in other ice-covered regions of the world
- a recognition that collaborative and cooperative R&D work makes good sense in some ice issue areas, and interest in possible JIP approaches from some companies
- a recognition of the importance of resolving any outstanding technical issues in a timely manner, despite the view that environmental and socio-economic factors may be of more consequence for future Beaufort Sea projects
- a recognition of the ice-related R&D work that has been carried out through PERD and other programs, since the downturn in interest in the Beaufort Sea seen in the late 1980s
- a warning about the need to manage expectations regarding potentially high levels of industry activity in the Beaufort Sea, at least in the short term, because most companies have no firm plans at present, and are just beginning to revisit possible opportunities in the area

On the basis of this assessment work, four specific ice-related R&D thrusts are recommended for further consideration, and a suggested logic framework outlined for each one of them. These R&D thrusts are intended to address high priority ice issues where there is either limited information, or where a front-end synthesis of information would be both timely and beneficial. They include:

- Multi-year design ice loads on fixed structures
- Ice loads on structures surrounded by grounded rubble ice fields
- Ice loads on vessels station-keeping in pack ice
- Engineering and operational implications of climate change on Beaufort ice conditions

The PERD Ice Structure Interaction Advisory Committee (ISIAC) is seen as fostering these ice-related R&D initiatives, with groups such as NRC-CHC and DFO-IOS carrying out much of the work. Other topic areas like ice scour, oil spills in ice, and EER systems for ice-covered waters are also viewed as ones of high importance, but are considered as being well handled at the present time through other programs and initiatives.

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1.0 Introduction

Over the past several years, there has been renewed interest in the hydrocarbon resources of the Canadian Beaufort Sea. It is well known that the region contains significant oil and gas reserves based on the results of exploratory drilling programs carried out in the 1970s and 1980s. During this period, more than 90 offshore wells were drilled in the area, with 21 significant discoveries being made. These discoveries confirmed the presence of about 1.5 billion barrels of recoverable oil and roughly 4 trillion cubic feet of gas in the Beaufort offshore. Potential hydrocarbon reserves in the area are considerably higher, and have been estimated to be in the range of 4 billion barrels of oil and 8 trillion cubic feet of gas.

Throughout the 1970s and early 1980s, various ingredients combined to support a bullish outlook for hydrocarbon developments in the Beaufort Sea, oil in particular. This atmosphere led to high levels of industry activity, substantial ice-related R&D initiatives, and rapid advancements in Arctic technology. However, no offshore development projects were actually undertaken. In this regard, there was a strong downturn in industry interest in the Beaufort in the late 1980s, caused by falling oil prices, high exploration and development costs, and the poor project economics that resulted. By the early 1990s, all offshore oil and gas activities in the Beaufort Sea were stopped, and the companies who had been involved turned their attention elsewhere.

Recently, industry has begun to revisit the opportunities that are available in Canada's frontier regions, including those in the Beaufort Sea. This interest has been stimulated by the decrease in hydrocarbon reserves being seen world-wide, significant increases in the price of oil and gas, and the northern gas pipeline that is now being planned. At present, various companies are undertaking reviews of the Beaufort's potential and thinking about new initiatives, with some companies being more advanced than others. For example, Devon will be drilling an offshore well in the shallow waters of the Beaufort Sea during the winter of 2005/06, the first one drilled since 1989. However, higher levels of exploration activity, and future developments, are by no means imminent.

Some of the technical challenges and uncertainties that are related to exploration and development activities in the Beaufort Sea have begun to re-surface, as a consequence of these new industry efforts. Many of the challenges involve ice problems since sea ice is the dominant environmental constraint in the Beaufort offshore. Over the past few years, some of these ice and technology issues have been addressed by PERD, but more-so by development projects in other parts of the world that are affected by ice, for example, in the Pechora Sea, the Caspian Sea and the offshore Sakhalin area. Fortunately, the Canadian expertise that was originally developed in conjunction with activities in the Beaufort Sea has been at the forefront of most of these recent international projects. However, the extreme ice conditions that are found in the Beaufort Sea present unique challenges, particularly the need to deal with multi-year ice.

Recognizing the resurgence of industry interest in the Beaufort Sea, NRC-CHC initiated a study to assess ice-related R&D requirements for future developments in the region, with PERD funding. The purpose of this work, which was carried out by B. Wright & Associates Ltd., is to identify the ice-related uncertainties and challenges that currently stand in the way of developing hydrocarbon resources in the Beaufort, ones that R&D may help to overcome. This information is required for input into the R&D planning cycle of PERD's Ice/Structure Interaction Committee. The results of the study are summarized in this report.

2.0 Objectives

The main objectives of this study are:

- To detail the ice-related uncertainties and challenges that are associated with developing Beaufort Sea hydrocarbon resources.
- To identify the relevant ice-related R&D work that could be performed to help mitigate or eliminate the uncertainties.
- To provide a plan for ice-related research that would be useful to support the design of future production systems in the Beaufort Sea

Although the work has focused on ice-related problems for Beaufort Sea developments, some of the other issues that have arisen as an outgrowth of study have also been identified.

3.0 Approach

The approach that was taken in the study work was subdivided into three main tasks. They are briefly highlighted as follows:

- review the key ice issues that were identified over the course of exploration activities in the Canadian Beaufort Sea during the 1970s and 1980s, in the context of their importance to production systems
- hold discussions with representatives of the oil industry to determine their perspective of ice-related R&D issues for potential development projects in the Beaufort Sea
- prepare a research plan to provide guidance on the type of ice-related research that would be most beneficial for future production systems, including specific research areas with clearly defined objectives

4.0 Background

4.1 General

The Beaufort Sea is a very remote region, lying well to the north of any major Canadian centers. Its physical environment is recognized as being one of the most hostile in the world. In winter, the area is characterized by low temperatures, a severe sea ice cover, and short daylight hours. The summer is more benign, with a short open water season, warmer temperatures, low to moderate winds, and small waves being typical. However, periods of poor visibility and fog, storms waves in fall, and the potential for heavy pack ice intrusions from the north are all factors of concern during the open water period.

Ice scouring on the seafloor, weak foundation conditions (in some areas), sub-sea permafrost, and the presence of hazards such as shallow gas and hydrates are additional factors of note. Along with these physical environmental constraints, the area's sensitive biological environment should also be recognized. Clearly, all of these environmental influences must be accommodated in the design and operation of any production systems that are intended for use in the Beaufort Sea.

A geographical reference map of the Canadian Beaufort Sea is given in Figure 4.1. The significant oil and gas discoveries that have been made in the region are also indicated in this figure.

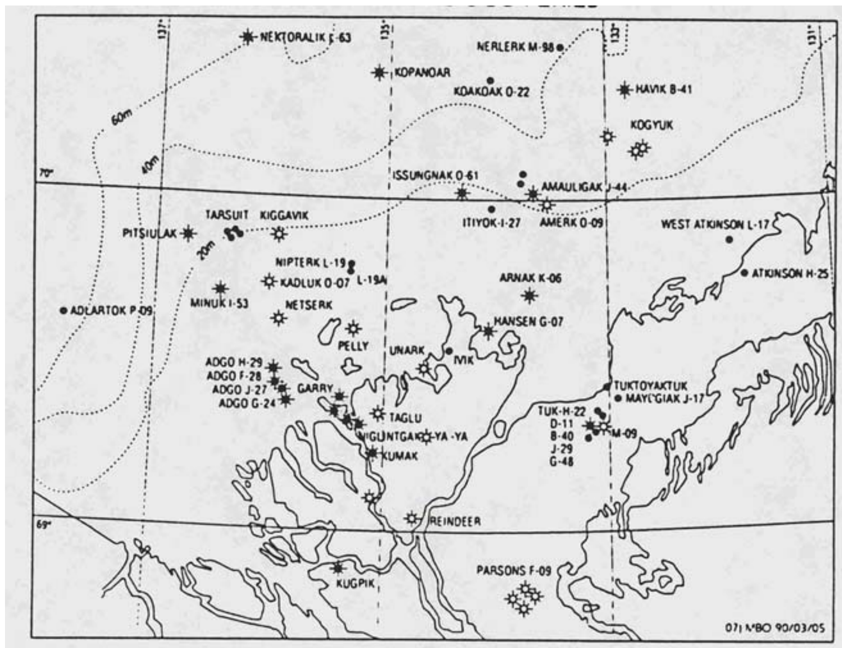

Figure 4.1: Geographical reference map of the Canadian Beaufort Sea, with the significant oil and gas discoveries made to date shown (from Dingwall, 1990).

This offshore region can be subdivided into several different areas, based on water depths and ice conditions, along with technology issues. These areas are briefly highlighted as follows.

- A shallow near-shore zone, from the coastline to about 20m of water, which is covered by landfast ice in winter. This is the offshore area where Esso Resources carried out most of their exploratory drilling, and where Devon will be drilling over the winter of 2005/06.
- An intermediate zone, from roughly 20m to 100m of water, which is covered by moving pack ice in winter. This is the offshore region where Dome Petroleum and Gulf Canada Resources carried out most of their exploratory drilling during the 1970s and 1980s.
- A deep zone over the continental shelf and slope, in water depths from roughly 100m to several hundred meters or more, which lies close to (and often within) the permanent polar pack in winter. Although no exploration activities have been undertaken in this deep water area to date, it does contain potentially large hydrocarbon reserves.

It is well known that significant exploratory drilling programs were conducted in the shallow and intermediate waters of the Beaufort Sea during the 1970s and 1980s, with Dome Petroleum, Esso Resources Canada and Gulf Canada Resources being the main players. Over this period, a good understanding of the ice and other environmental conditions in the region was gained through data acquisition programs, R&D initiatives and direct operating experience. Novel drilling systems were designed, constructed and employed to drill wells on both a seasonal and year round basis. Various production systems were also conceptualized and engineered, but never put into place. A great deal of ice-related knowledge, technology and "know-how" for the Beaufort was developed at the time, which has been subsequently used to assist with in-ice projects elsewhere in the world. However, a number of important ice issues were never fully resolved, and still remain today.

In order to provide some context for the R&D requirements that are highlighted later in this report, a brief overview of ice conditions in the Beaufort Sea is first given, since ice-related problems are the main focus of this study. Highlights of the technology that has been used in the Beaufort are outlined next, to give some sense for what was actually achieved. A few comments about the ice-related issues and uncertainties that were seen at the time of these earlier activities are provided within this background information, along with some of the R&D needs that have been identified in previous work.

4.2 Overview of Ice Conditions

The primary environmental constraint in the Beaufort Sea is sea ice, since the area is normally ice covered for at least nine months of the year. The annual ice conditions can be subdivided into four basic periods, freeze-up, winter, break-up, and the short open water season in summer. During the freeze-up, winter and break-up periods, three different ice zones are evident in the general region, as shown in Figure 4.2. They include the landfast ice zone, the transition (or seasonal) pack ice zone, and the permanent polar pack. Since the ice conditions in these ice zones are very different, they represent distinct types of in-ice operating regimes. In this regard, any planned exploration or development activities in these three ice zones (and their water depth ranges) will likely involve somewhat different types of technology.

In the landfast ice zone, which typically covers the area from the shoreline to about 20m of water, the following ice-related points should be noted:

- the landfast ice cover is comprised of first year ice and contains significant areas of ridged and rubbled ice, particularly towards its outer edge
- the landfast ice is quasi-stable over the course of the winter, but it does undergo sporadic movements, with typical displacements of a few meters to tens of meters (or more)
- extreme ice feature interactions within the landfast ice zone are unlikely (e.g. with large multi-year ice floes), since the presence of very thick ice features is limited by water depth
- seafloor scouring from first year ridge keels is quite common in the mid to deeper water parts of the landfast ice zone, in water depths from roughly 10m to 20m
- various on-ice construction and transportation activities are generally feasible in landfast ice, at least in its smoother near-shore areas
- the landfast ice zone is a comparatively easy part of the Beaufort Sea to design structures for, and to operate in, but is certainly not without its particular ice issues

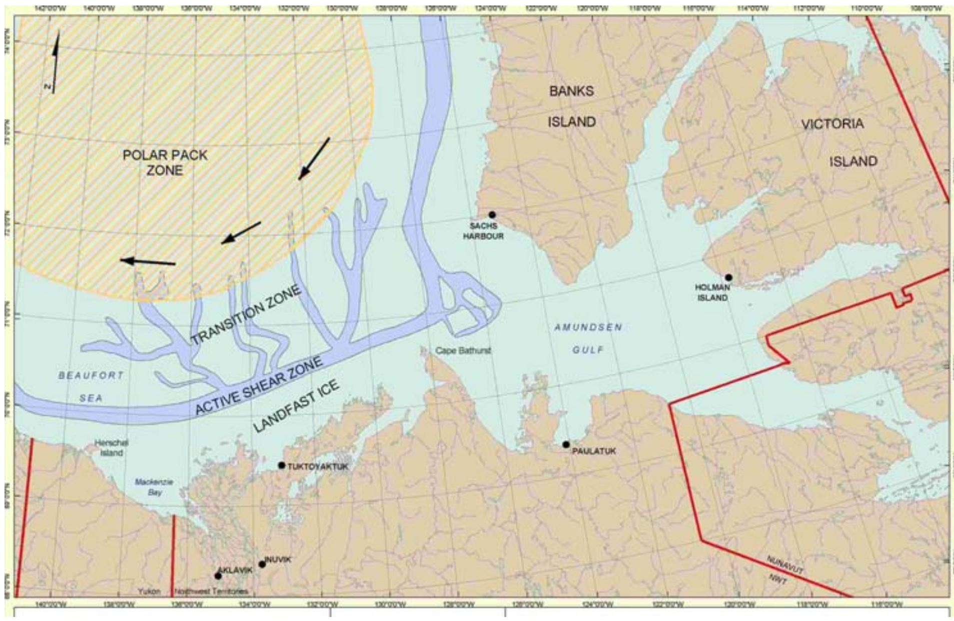

Figure 4.2: Winter ice zones in the Canadian Beaufort Sea.

The transition ice zone, which includes the intermediate water depths of the Beaufort Sea, offers a more difficult array of ice problems to deal with. In this area:

- the pack ice cover is mainly comprised of first year ice floes, but it can contain significant concentrations of multi-year ice (and very rarely, some ice island fragments)
- this pack ice is in near continual motion throughout the winter period (unlike the quasi-stable landfast ice cover), and can move in any direction over time scales of days
- during winter, the pack ice in the transition zone can contain leads and openings when the winds are offshore, but it can also be "tight" and subject to significant ice pressure events when the winds push the ice cover against the landfast ice edge
- extreme ice feature interactions, involving large multi-year floes that can contain ridges of 20m to 30m in thickness (or more), are much more likely in the transition zone than in the Beaufort's shallower water areas, and are a key concern for the design of fixed structures
- seafloor scour by first and multi-year ridge keels is also prevalent in the shallower parts of the transition zone, in water depths from roughly 20m to 35m
- in-ice (or on-ice) construction activities are very difficult and generally not feasible in the transition zone in winter, due to its moving ice cover
- this is generally a more difficult area to design exploration and production systems for, and to operate in, as compared with the more sheltered landfast ice zone

The deeper waters that lie further northwards offer even more significant ice-related challenges. These northerly areas are close to or under the polar pack and, to date, are totally unexplored. The polar pack ice in the deeper water of the Beaufort Sea remains mobile throughout the winter, and the multi-year ice that comprises the polar pack ice cover is the obvious design issue. A positive aspect in the deeper parts of the Beaufort is that there is no seafloor ice scour, due to water depth.

A generalized schematic that shows a representative cross-section of the Beaufort Sea's landfast and transition (or seasonal) ice zones in winter is presented in Figure 4.3. A few photos of typical ice conditions in these ice zones are given in Figures 4.4 and 4.5, to provide a visual feel for them.

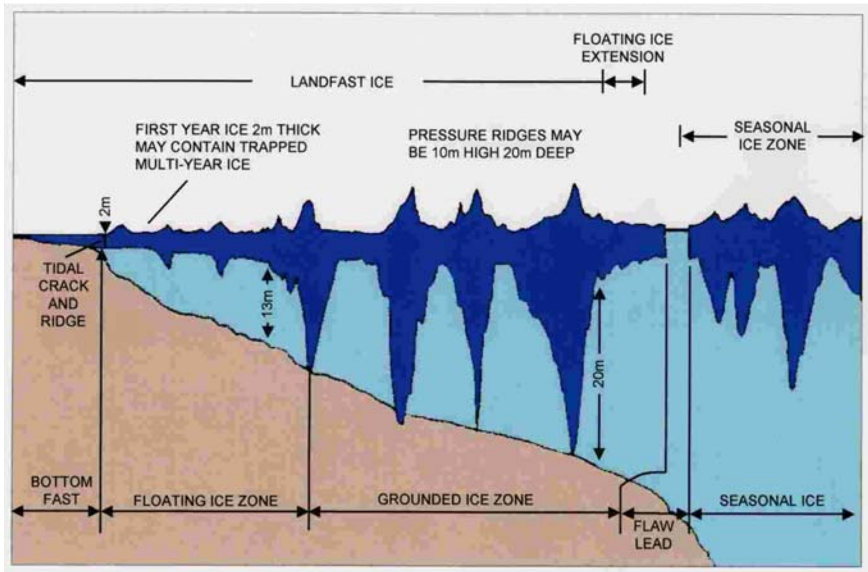

Figure 4.3: A schematic cross-section of the landfast zone ice in winter.

Figure 4.4: Representative views of ice conditions in the landfast ice zone in winter.

Figure 4.5: Representative views of ice conditions in the transition ice zone in winter.

4.2.1 Freeze-Up Period

The Beaufort Sea normally begins to freeze-up in early to mid October, with new ice forming in its shallow near-shore waters and progressively growing seawards. At the same time, or shortly thereafter, new ice also begins to form in the deeper water areas adjacent to the permanent polar pack, spreading southwards from there, and quickly merging with the shoreward ice cover. By late October, the entire region is generally covered by thin pack ice that has a blend of ice thicknesses, up to 30 cm or so. During this early stage of freeze-up, the ice cover remains mobile throughout the Beaufort, except in some of the sheltered bays and inlets along its coastline. Leads, openings and some rafted areas are common in the newly forming ice cover at this time, although ridges are infrequent, because the ice is still quite thin.

It is noteworthy that polar pack ice intrusions from the north, and strong storm winds, are most common at this time of the year. Storm winds can disperse the newly growing ice cover and create large waves, while old ice intrusions can quickly turn easy ice conditions into an ice situation that is very severe. Several representative views of ice conditions during the freeze-up period are shown in Figure 4.6.

The early freeze-up period is of little consequence in terms of the design of production systems, except for the old ice intrusions and storm wave events that may occur during this time period. However, it is of considerable importance for various construction, structure deployment (or de-mob) and supply operations that are based on the use of conventional vessels, since these types of operations will be impeded or precluded, even by light ice.

Figure 4.6: Representative views of ice conditions during the freeze-up period.

Over the course of the drilling activities that were carried out in the Beaufort during the 1970s and 1980s, a number of ice-related issues began to arise for the early freeze-up period, primarily in relation to operability in early freeze-up conditions. Some of the more important considerations are briefly highlighted as follows:

- how could some of the operations (construction, supply, mob and de-mob, etc.) that were normally conducted in open water conditions be extended into the freeze-up period
- what blend of equipment (conventional or ice-strengthened vessels) and ice management support would allow this extension of operations, and how much additional working time could be gained
- in the event of an emergency situation, how could personnel be safely evacuated from offshore structures in thin moving ice conditions
- would newly forming ice prevent old ice floes from entering the shallower water areas of the Beaufort, thereby reducing the potential for old ice interactions in the near-shore zone
- would the near-shore ice conditions that developed during the freeze-up period impede or preclude vessels that were operating further offshore from accessing their over-wintering sites (in Tuk harbor, McKinley Bay, Herschel Basin, etc.)

As the freeze-up period extends into November and early December, ice conditions in most parts of the Beaufort Sea progressively become more difficult in terms of the thicknesses and degree of ridging in the ice cover, precluding any operations with vessels that do not have ice strengthening. Air temperatures continue to decrease, along with the number of daylight hours, which fall to zero with the onset of the polar night. Over this time frame, the landfast ice cover begins to take hold in the Beaufort Sea's shallower water areas, moving northwards in a series of discrete steps. This progression is caused by periodic onshore winds that move growing pack ice in the transition zone shoreward, where it interacts with more southerly landfast ice edge. This process creates bands of ridges where the fast ice edge resides at the time, with some of the keels of the ridges being deep enough to ground on the seafloor. These ridge zones (see Figure 4.7) tend to stabilize the ice cover lying shoreward of them. By late December, the landfast ice zone typically extends between 50 and 60 km offshore to the 20m water depth contour, where it generally remains stable for the rest of the winter.

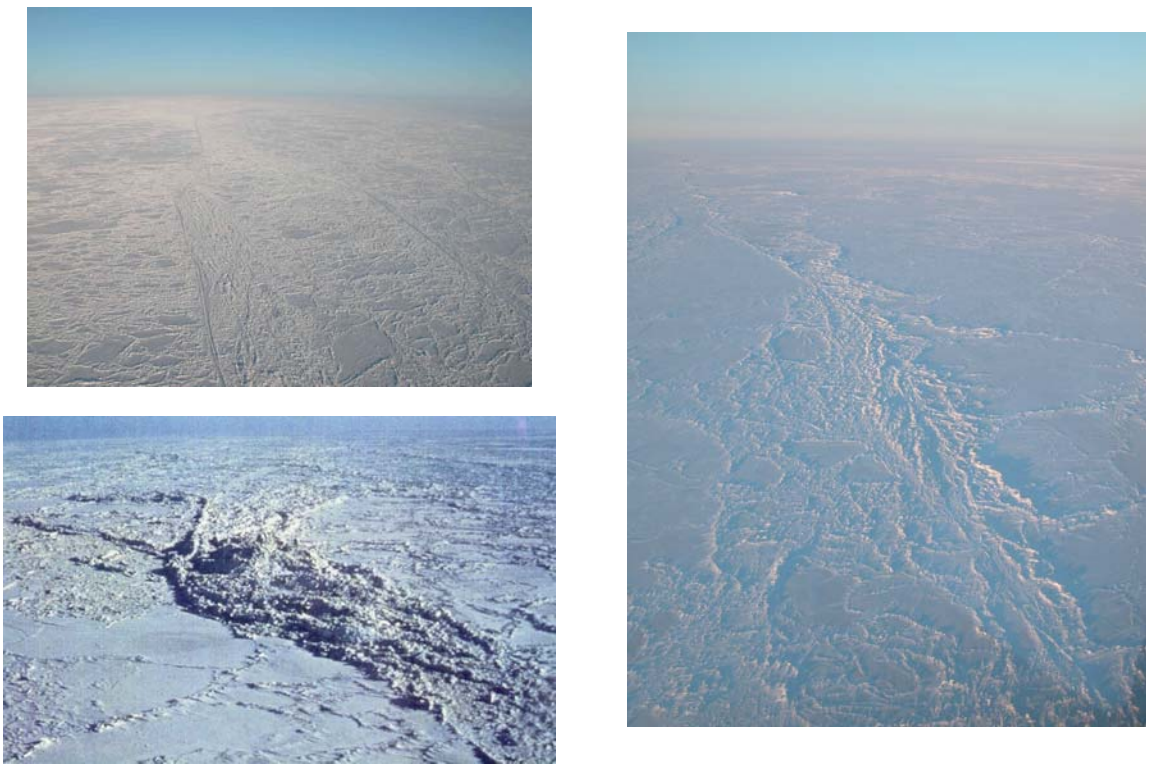

Figure 4.7: Views of the types of ridge fields that stabilize the landfast ice cover, as it grows seaward to the 20m water depth contour over the course of the freeze-up period.

Near-shore, the landfast ice cover is generally quite smooth, but it typically contains increasing numbers of pressure ridges in its middle portions and outwards, towards its outer edge. Most of the ridges and rough ice areas that are found within the landfast ice zone are formed during the mid to late freeze-up period, and its overall complexion changes little over the subsequent winter period, with the exception of its thickness.

During the mid to late stages of freeze-up, the ice in the Beaufort's transition zone also undergoes significant ridging and rubbling, due to relative motions within its moving pack ice cover. At this time, onshore movements of the pack ice can cause ice pressure events of varying durations and intensities, which can be a serious impediment to various marine operations, even those involving well powered ice-capable vessels.

Based on some of the experiences that were gained with offshore activities in the Beaufort during the mid to latter parts of the freeze-up period in the 1970s and 1980s, a number of important considerations arose. They included both design and operational issues, and are briefly highlighted as follows.

Shallower Water Depths – the Landfast Ice Zone

- when will landfast ice form at a particular location, and thereby offer a "calmer" and more protected in-ice operating environment for a structure

- what structure freeboard and form is needed to prevent ice pile-up and overtopping events on a structure's working surface when the ice cover is still mobile (and also, green water overtopping during storm wave events)

- when will grounded ice rubble first form around a structure, how stable will the grounded ice rubble be, and will it reduce ice loads and the potential for other adverse ice effects

- when can ice roads first be built and utilized, and in what water depths are roads, aircraft landing strips and so forth feasible to construct, recognizing ice thickness and roughness constraints, and what role can spray ice technology play in these types of activities

Intermediate Water Depths – the Transition Ice Zone

- how late can in-ice drilling operations with very capable floating systems like the Kulluk actually proceed into the late freeze-up and early winter periods, and how long can in-ice station-keeping operations be successful (at that time, with a view to required relief well drilling capabilities)

- can potentially hazardous ice conditions be adequately detected, monitored and forecasted in the range of adverse environmental conditions on hand (e.g.: fog, darkness, snow and so forth)

- how to deal with the potential for oil spills in the ice conditions that are expected, and also with EER requirements, particularly for bottom founded drilling systems that do no have attendant icebreaking vessels

Again, mid to late freeze-up ice conditions are of little consequence in terms of ice loads on the Beaufort Sea structures designed for year round operations, but in the past, were of more importance for floating drilling system operations, and various operational considerations at this time of the year.

4.2.2 Winter Period

The first year ice comprising the ice cover in the Beaufort Sea's landfast and transition ice zones normally grows to thicknesses of between 1.6m and 1.8m over the course of the winter period. A large range of first year ridge sizes is also commonly seen in these areas in winter. For example, in the landfast ice zone, many ridges with sail heights in the range of 3m to 4m (or more) can be seen which are grounded in 10m to 20m of water, as noted above. These types of ice features can scour the seafloor, but are not a real threat to structures in the landfast ice, due to its limited movements, and the fact that grounded ice rubble fields usually form around them.

Multi-year ice floes and on rare occasions, small ice island fragments, may also be incorporated into the deeper parts of the landfast ice zone in some years, after drifting in the during the fall ice freeze-up process. However, the thickness of these extreme features is limited by water depth and should they occur, they are much less severe than what can be found drifting in the pack ice cover further offshore, in the Beaufort's intermediate to deeper waters areas. Figure 4.8 shows examples of some of the types of extreme ice features that can be found in the landfast ice zone in winter.

Figure 4.8: A large grounded first year ridge (upper left), a multi-year ice floe (middle), and an ice island fragment (lower right) observed in the Beaufort's fast ice zone in winter.

In the transition zone pack ice cover, the range of extreme ice features that can be encountered is more severe. They include very large first year ridges, substantial multi-year ice features and, on rare occasions, ice islands (or their fragments). These types of ice features, particularly multi-year ice or ice island formations (see Figure 4.9), are of high importance in terms of potential design ice loads on fixed structures in the intermediate and deeper waters of the Beaufort Sea. Previous studies have shown that multi-year ice floes can be sizable (a few kilometers in diameter) and very thick over most of their area.

Figure 4.9: Extreme ice features that can be found drifting in the Beaufort Sea's transition ice zone in winter (multi-year ice left and center, and ice island fragment on the right).

In the mid 1980s, so called multi-year ice hummock fields were being cited as the extreme ice features that could give rise to the governing design global ice load on Beaufort Sea production structures located in the transition zone. Ice islands were also recognized as being hazardous, but were considered to be rare ice loading events that would be identifiable well in advance. At the time, the deemed response to any ice island occurrences would be a shut down in operations and evacuation of people, well in advance of a potential ice island interaction. However, as industry's interest in the Beaufort Sea began to wane, these topic areas were not pursued too much further.

Clearly, a substantial experience base has been developed with the design and operation of various drilling structures in both the Canadian and Alaskan Beaufort Seas in winter. However, a number of ice-related uncertainties and issues remain, which are highlighted as follows:

- the nature and extent of grounded ice rubble fields that may form around structures in first year ice, when they may occur, and their influence in terms of mitigating ice load levels

- multi-year ice feature statistics, including multi-year ice hummock fields, and the risk of interactions between these types of extreme ice features and offshore structures

- the ice loads that may result from direct interactions between multi-year ice floes with "bare" structures, and the full scale ice failure behaviors underlying these loads

Other key issues that were evident during previous Beaufort Sea operations, and still are, include:

- oil spill behavior and clean-up in moving winter ice conditions
- EER approaches in moving winter ice

Additional topic areas that have always been of high interest for potential offshore developments include:

- low cost offshore production structures
- seafloor ice scour from first year and multi-year ice features, and how best to design sub-sea pipelines and other seafloor facilities to contend with this risk
- the possibility of year round vessel operations in ice, including the tanker export option

4.2.3 Break-up Period

Ice break-up in the near-shore waters of the Beaufort Sea normally begins in the mid June to early July period, with near total ice clearance typically seen in water depths to about 20m by late July. The break-up process starts with a general weakening of the ice cover, together with melting of its surface, caused by rising air temperatures and long daylight hours. Immediately adjacent to the shoreline, significant melting is first seen, which is enhanced by run-off from the Mackenzie River in many areas. Concurrently, the pack ice in the transition zone to the north of the landfast ice begins to move offshore, under the influence of winds from the east and south. Large sections of the landfast ice cover tend to fracture and then drift northwards during this period. Diminishing ice concentrations and floe sizes are typical as break-up proceeds. The ice break-up process normally clears all of the ice from the shallow southern portions of Beaufort Sea by late July, and from the more northerly intermediate water depth areas over the early August period.

Some of the more important issues that arose during earlier Beaufort Sea activities in relation to the break-up season included:

- the question of whether spray ice platform lifetimes could be extended into the break-up ice period, and perhaps beyond into the open water period (primarily from the standpoint of relief well drilling system capabilities)
- the question of how early operations with "low or no ice class vessels" could begin, and the levels of ice management that may be needed to enhance these types of operations.

The experience that was gained at the time showed that earlier starts to various offshore operations in the Beaufort Sea were generally more difficult to achieve than extensions to operations over the freeze-up period. In this regard, the large, thick and heavily deformed ice floes seen during break-up presented much heavier and often more variable conditions than those seen in fall.

4.2.4 Open Water Period

In the southern Beaufort Sea, the open water season usually lasts for about three months, from mid July to mid October. In terms of its physical oceanography, the region is relatively mild when compared to most other offshore areas of the world. In summer, typical wave heights are low, in the range of 1m or less. Extreme wave of 6m to 7m can occur during severe fall storm events but are rare, since wind fetches are usually limited by ice. Currents in the area are also typically weak, in the range of 0.2 m/sec or less. However, the Mackenzie River outflow has a strong influence on currents in the Beaufort's near-shore waters, particularly in the area of its outflow from the Delta.

Although the open water season is usually quite quiescent, heavy pack ice can move into the near-shore waters of the Beaufort Sea under the influence of strong winds from the northerly quadrants. In part, these ice intrusions result in the high degree of variability that is seen in the length of the open water season that is seen from year to year. When they do occur, most commonly in fall, these ice intrusions can bring thick remnant first year ice and multi-year floes from the polar pack into the Beaufort's coastal waters and result in very adverse ice conditions, particularly in the transition zone area. Fortunately, this heavy pack ice generally tends to ground in 15m to 20m of water as it moves ashore, and is a lesser concern in the Beaufort Sea's shallower inshore waters. In these shallow water areas, any drifting old ice floes that may be found are typically small, and their thicknesses and degree of ridging not excessive.

Past experience has shown that the Beaufort Sea's open water season is not very predictable. Ice break-up and freeze-up time frames can be earlier or later than normal in any given year, and pack ice intrusions can occur at any time. In this regard, and also in terms of year round ice conditions, the potential effects of climate change on Beaufort Sea ice conditions has become a key issue. The open water window that is available to mob and de-mob vessels and structures into the Beaufort around Point Barrow, or from the east, is another matter of importance. Also, the question of open water storm waves should not be overlooked, particularly if more extensive open water situations and potentially larger storm wave events become a consequence of climate change.

4.3 Overview of Previous Exploration Systems

The design and operation of exploration systems in the Beaufort Sea required new knowledge and special technology, most of which has been developed in Canada. When offshore activities were first undertaken in the early 1970s, it was not known how the technology would unfold, only that new methods would be required, due to the severity of the Beaufort's environment. Despite the ice and other environmental constraints, industry developed the capabilities to safely conduct drilling operations in the Beaufort, and did so from the mid 1970s to late 1980s.

Bottom founded structures were used to drill wells in the Beaufort Sea's shallow to intermediate water depths on a year round basis, while floating drilling systems were employed to work in its mid to deeper water areas seasonally. In order to resist the large forces imposed by the winter ice cover, the bottom founded structures had to be massive, with their size and weight providing the necessary sliding resistance to counteract lateral ice loads. In contrast, the mooring capability of the floating drilling systems limited their operations to the late break-up through late freeze-up period, when ice conditions were comparatively light.

4.3.1 Bottom Founded Structures

Artificial Islands

Artificial islands were the first type of structure used for exploratory drilling in the Beaufort Sea. Initially, they were built in the sheltered near-shore areas of the Beaufort, where shallow waters and early landfast ice growth were characteristic. Some were constructed by dumping gravel fill through the ice, but most were built from locally dredged sand during the open water season. They had typical surface dimensions of about 100m in diameter and generally low freeboards, in the order of a few metres, sloping down to the waterline. Drilling equipment, other topsides facilities and consumables were mobilized to the islands once they had been constructed, either by barges in open water or over ice roads in winter. Figure 4.10 provides views of some of the artificial islands that were constructed for offshore drilling in the Beaufort Sea.

Figure 4.10: Several artificial island drilling structures in the Beaufort Sea.

The artificial islands built in shallow water areas, which required modest fill volumes, performed well, and as experience was gained, the technology was extended further offshore. However, with increasing water depths, the fill volumes needed for island construction became substantially larger, and their costs considerably higher. Also, the time frame needed to build an artificial island in waters depths in the range of 15m or more exposed them to the potential for storm waves and significant erosion near the end of the open water season in fall, during the critical phase when they were nearing completion. The deepest artificial island was constructed at the Issungnak site, in 18m of water, and took two years to build. As it was being completed in the fall of the second year, a considerable part of its above water volume was eroded during a fall storm wave event, although it still functioned well as a drilling platform the following winter.

It is well known that grounded ice rubble fields invariably formed around these artificial islands, as the result of ice failures against their beaches during the early freeze-up period, when the newly growing ice cover was still mobile. In shallow water locations, where the landfast ice stabilizes shortly after freeze-up, these rubble formations were generally only a few tens of metres in extent, and the ridge sail heights they contained were not particularly high. However, in the deeper water areas where the ice remained mobile for longer, the rubble fields that surrounded artificial islands were considerably larger, a few hundred metres (or more) in extent. Sizable ridges and hummocks were also seen within these larger ice rubble formations which were firmly grounded on the island slopes. Once formed, these grounded ice rubble fields remained stable until the landfast ice cover broke up the following spring. They were beneficial in the following two ways:

- the rubble that formed immediately adjacent to artificial islands over the early stages of freeze-up (when the ice was thin), provided a buffer against direct ice action, moved the ice failure zone outwards, and provided protection against potential ice ride-up or pile-up onto their working surface

- later in the winter, once landfast ice had formed around them, they promoted mixed modal ice failures (at lower load levels than crushing) at their outer boundary, and also tended to absorb some of the applied ice loads, through load transmission to the seafloor

It is noteworthy that the North Star oil production platform, which has been in service since the late 1990s in 12m of water in the Alaskan Beaufort Sea, is a large artificial island.

Tarsuit CRI

The next type of bottom founded structure that was designed for offshore drilling operations in the Beaufort Sea was the Tarsuit Caisson Retained Island (CRI). This concept was a logical extension of artificial island technology, and was developed to reduce costs and shorten the construction time frames as exploration moved into the Beaufort's intermediate water depth areas. The Tarsuit CRI was a hybrid structure, consisting of four shallow concrete caissons that were set down on a large sub-sea berm. The caissons were roughly 70m in length, 15m in width and 11m in height, and were placed to form a square enclosure on a pre-constructed sand berm, built to a height of 6m below sea level. The hollow caissons and the central core area between them were then filled with sand, to provide adequate sliding resistance against horizontal ice loads.

The Tarsuit CRI was deployed at a drilling location in about 20m of water. As configured, it had a surface area of 70m x 70m, which was small, and an above water freeboard of 5m. The drilling rig and stacked trailer modules that formed its topsides were mobilized to the CRI by barge in the fall, and then erected on it. The Tarsuit CRI was designed to withstand the forces from both first-year and multi-year ice and, in concept, for storm wave events during the Beaufort Sea's open water season. Views of the Tarsuit CRI are shown in Figure 4.11 in both winter ice and open water wave conditions.

Ice loads measured on the structure when it was drilling, and also over the following winter, showed the beneficial effects of the grounded rubble fields that formed around it. The first ice pad was also built in the rubble at Tarsuit to provide relief well drilling capability. It is interesting to note that storm wave effects on this structure were actually more of a problem than ice action.

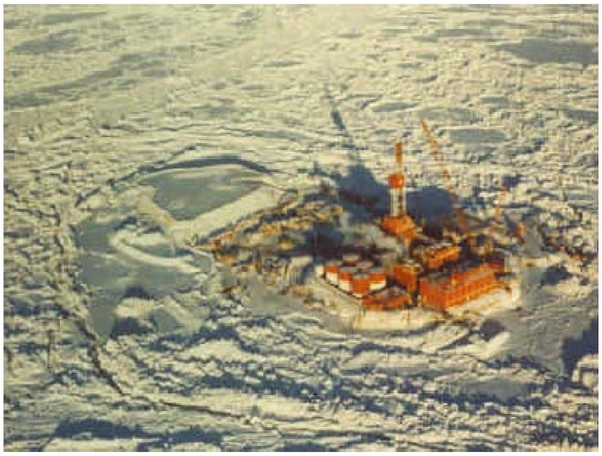

Figure 4.11: Views of the Tarsuit CRI and its relief well pad in landfast ice conditions in winter (upper) and in storm wave conditions during the open water season (lower).

Esso CRI

Esso designed and constructed a second type of caisson retained island for drilling operations in the Beaufort Sea, shortly after the Tarsiut CRI was used. Again, this caisson was intended for use in the shallow to intermediate water depth range (12m to 25m), where artificial islands were costly and time consuming to construct. It was a steel structure that consisted of eight sides, held together by a cable system, to form an octagonal ring. When deployed, the steel ring was placed on a pre-built sub-sea berm and filled with dredge sand to achieve the necessary sliding resistance. The surface diameter of this CRI was about 90m. Its draft was 8m to the top of the berm on which it sat, and it had an above water freeboard of 5m. There was a small outward sloping ice and wave deflector at the top of its outer walls. As with artificial islands and the Tarsiut CRI, the drilling rig and trailer modules that formed its topsides were mobilized to the structure by barge in the fall, and then erected on it. The Esso CRI was designed to withstand the forces from first-year and some multi-year ice interactions. In shallow water deployments, it was also intended to withstand storm wave effects during open water operations.

This CRI was used to drill wells at several locations in the 14m to 25m water depth range, where it was exposed to moving pack ice well into the late freeze-up period. As a result, large grounded rubble fields formed around it, as shown by the views in Figure 4.12. These rubble fields, which were several hundreds metres in extent, were heavily deformed, with high ridges and hummocks in many areas. After their formation, they remained stable until break-up. On one occasion, in a unique freeze-up circumstance, some ice blocks did overtop part of the Esso CRI.

Figure 4.12: Views of the Esso CRI and the grounded ice rubble fields that formed around it.

SSDC

The SSDC (single steel drilling caisson) is another structure that Dome used to conduct drilling operations in the Beaufort Sea in the 1980s. It was constructed from an existing tanker by cutting off the vessel's bow and stern sections, and strengthening the remaining vessel mid-body along its sides and bottom, to withstand ice loads and other types of forces. In terms of its dimensions, the SSDC is about 160m in length, 55m in width, and 25m in overall height. It is actually a shallow caisson that, when first used in the Canadian Beaufort Sea, was deployed on a large submerged berm at a draft of 8m. This resulted in a structure with an above water freeboard of about 17m.

The SSDC was developed for use as a year round drilling platform at locations in the 20m to 40m water depth range. In principle, it was designed to be capable of withstanding the loads from first and multi-year ice in the transition and landfast ice zones, as well as the effects of storm waves. However, for its first two deployments at locations in the Beaufort's transition zone, spray ice pads were constructed in the rubble fields that formed around it, to increase its resistance for potential multi-year ice floe interactions. Since no old ice interactions actually occurred during these deployments, the SSDC only gained experience with first year ice action at these sites.

After two years of use for drilling operations in the Canadian Beaufort Sea, over the winters of 1982/83 and 1983/84, a large steel mat was constructed for the SSDC. This mat took the place of the dredged sub-sea berms that the unit was set on in its first two deployments, and allowed the structure to be used for drilling operations in the landfast ice off Alaska, where dredging is not permitted. The SSDC drilled five wells in the Alaskan Beaufort, in 11m to 21m of water.

Several views of the SSDC are shown in Figure 4.13. Here, it should be noted that Devon is using the SSDC (now called the SDC) to drill their Paktoa well in the Canadian Beaufort Sea during the 2005/06 winter period. This location is in 12m of water, and is situated in the landfast ice zone in winter.

Figure 4.13: Views of the SSDC and its ice pad in winter pack ice conditions in the Canadian Beaufort (left), and as deployed in the Alaskan Beaufort Sea with its MAT (right).

Molikpaq

The Molikpaq is a mobile arctic caisson that was designed and constructed for year round drilling operations in the Beaufort Sea. It is a deep steel caisson with a hull depth of 29m, base dimensions of 111m x 111m, and deck dimensions of 73m x 73m. As built, the lightship displacement of the caisson was 31,000 tonnes, with a lightship draft of 5.2m. When operating in the Beaufort Sea, the Molikpaq was generally deployed on a sub-sea berm. Its internal core was filled with sand to provide a high level of sliding resistance against horizontal loads. The structure was designed to withstand the forces from both first-year and multi-year ice interactions, as well as the extreme storm waves that can occur in the Beaufort Sea open water season.

The water depths in which the Molikpaq could operate ranged from 10m to 40m. For shallow water deployments, the caisson was set directly on the sea floor, for example, at the Isserk location in 12m of water. At deeper locations, a sub-sea berm was built to the necessary height to provide an acceptable on bottom weight and above water freeboard for the structure, once it was deployed. At the Tarsuit P-45 and Amauligak I-65 locations, in water depths of about 35m, the caisson was set down on sub-sea berms at a draft of about 20m. This resulted in an above water freeboard of roughly 10m to the Molikpaq's main deck, and 15m to the top of its upper wall ice deflector.

Due to the Molikpaq's deep set down draft at these two Beaufort Sea drilling locations, grounded ice rubble did not form around the caisson, and it was exposed to direct ice action from moving winter pack ice over the course of two winter seasons. This included interactions with multi-year ice floes at the Amauligak site that occurred during winter of 1986. In this regard, it is important to note that the Molikpaq is the only offshore structure to experience multi-year ice loading events to date. Although the old ice floes that impacted the structure were not particularly severe, the ice load levels were high in comparison to first year ice loads, and the Molikpaq was severely tested.

Representative views of the Molikpaq in moving pack ice conditions are given in Figure 4.14, which include ones of multi-year ice crushing against the caisson. After working in the Canadian Beaufort during the 1980s, this caisson was sold and is now being used as a production platform in the ice-covered waters off Sakhalin Island.

Figure 4.12: Views of the Molikpaq in moving winter pack ice in the Beaufort Sea's transition zone. Because no grounded ice rubble fields formed around this caisson when it was deployed at deep draft (20m), it experienced direct ice action against it, including a few multi-year ice interaction events.

__*Spray Ice Platforms*__

In the late 1980s, spray ice technology was also developed and utilized to construct ice pads that were used as low cost drilling platforms in the Beaufort Sea. Two such ice pads were built in the Canadian Beaufort, and a considerable number off the Alaskan North Slope, in water depths to about 8m. These spray ice pads performed well, but were clearly temporary structures, since they melted in the summer. Several views of spray ice pads are shown in Figure 4.15.

Figure 4.15: Views of the spray ice pads used as drilling platforms in the Beaufort Sea.

The artificial islands and caisson structures that have been highlighted above generally performed well, and allowed year round drilling in the Beaufort Sea's landfast and transition ice zones. As their deployment locations progressed further offshore from the shallow to the intermediate water depths of the Beaufort, they were exposed to moving ice for the majority of the freeze-up period, and at sites in more than 20m of water, have withstood moving pack ice throughout the winter. The full scale ice/structure and ice load information acquired through monitoring programs on and around these structures has provided invaluable input for design improvements and technological advancements.

However, it is important to note that none of the structures used in the transition zone experienced the type of extreme design ice features that should be expected for production platforms deployed over 20 to 30 year development project time frames. The Molikpaq caisson came the closest, since it did experience five multi-year ice floe interactions during the winter of 1986. However, the old ice features that it encountered were by no means extreme. Also, although sloped structures are preferred by some, as a means of reducing ice loads from extreme ice features through flexural ice failures, there is no full scale experience with them.

4.3.2 Floating Drilling Systems

Drillships

Relatively conventional drillships were used for exploratory drilling in the mid to deeper water areas of the Beaufort from 1976 until the late 1980s. Although these vessels were ice strengthened to Baltic Class 1A Super levels, their operating season was limited to the open water and early freeze-up periods. Four drillships (Canmar's Explorer fleet) were used in the Beaufort Sea, all having displacements of about 15,000 tonnes and overall dimensions of roughly 100m x 20m x 9m. Each vessel was deployed with an eight point mooring system comprised of 2 3/4 " wire lines (four bow and four aft) that came off the deck and through the waterline (except for the Explorer 4, which had underwater fairleads). These lines were equipped with remote anchor releases (RARs) that allowed the drillships to quickly disconnect from their anchors and move off location, should difficult ice or storm wave conditions occur. The overall mooring system capacity of the drillships was in the order of 100 tonnes. Once moored, these drillships were aligned in a fixed direction and could not reorient themselves in response to changing ice drift directions without moving off location. From an ice management perspective, typical support for drillship operations consisted of one or two CAC 4 supply vessels and at times, the Robert Lemeur (CAC 3) and/or the more highly powered Kigoriak (CAC 2) icebreakers.

Canmar's drillships conducted drilling operations at more than 40 different sites in the Beaufort and Chukchi Seas, in water depths ranging from roughly 20m to 80m. The majority of these wells were scheduled for the summer and early fall periods, when open water and relative light ice conditions are common. However, with ice management support, the drillships sometimes worked in moderate to relatively high ice concentrations during ice intrusions, provided the pack ice was managed into small pieces and could easily flow around them. Representative views of drillship operations in Beaufort Sea ice are shown in Figure 4.16

Figure 4.16: Views of drillships working in light managed ice conditions.

Kulluk

The Kulluk is a conical drilling unit that was purpose built for extended season drilling operations in the Beaufort Sea. It was designed as a floating barge with integral drilling (and other) facilities on its deck, a capable mooring system, and a strong hull that was strengthened to Arctic Class IV (CAC 2) standards. The Kulluk was designed with a unique circular shape and an inverted conical hull form, to accommodate ice action from any direction equally, and to fail the oncoming ice in downwards flexure at low load levels. It was also designed with an outwards flare near the bottom of its hull, to ensure that broken ice pieces would clear around it and not enter its moon-pool or get entangled in its mooring lines. It has a radially symmetric mooring system comprised of twelve 3½ " wire lines that run through the hull to underwater fairleads near the bottom of the Kulluk's hull. Each line was connected to large anchors (typically 15 tonne Bruce anchors) and had remote anchor releases (RARs). The overall mooring system was designed to withstand global ice loads of 750 tonnes while drilling operations were underway, and allow station-keeping in storm waves up to 7.2m. In terms of its dimensions, the diameter of the Kulluk is 81m at its main deck level and about 70m at the waterline. It has a height of 31.5m from the bottom of the hull to its elevated drill floor, and a freeboard of about 5m to its gunnels. The Kulluk's minimum and maximum operating drafts are 10m and 12.5m, respectively. The vessel's lightship displacement is 17,510 tonnes and it has a variable load capacity of about 7,000 tonnes.

When it was operating in ice, the Kulluk was always supported by very capable ice management vessels. The support fleet consisted of the Terry Fox and Kalvik icebreakers (25,000 HP CAC 2 vessels), and the Ikaluk and Miscaroo AHTS vessels (also CAC 2 icebreakers, with about 15,000 HP.) Two to three of these vessels typically supported the Kulluk when it was drilling, depending on the severity of the ice conditions. It is important to note that ice management support was a key contributor to the overall success of the Kulluk, and enabled drilling operations in very heavy ice conditions.

The Kulluk was used to conduct exploratory drilling operations in the Beaufort Sea in its deeper water areas (20m to 60m) from 1983 until the early 1990s. During this period, it worked in a wide range of pack ice and open water conditions, from late May until late December, and significantly extended the drilling season that was available to drillships. The Kulluk has been in "cold storage" in a sheltered location in the Beaufort Sea since it last worked off the Alaskan coast in 1993. Several views of the Kulluk and its support icebreakers during drilling operations in ice are shown in Figure 4.17.

4.4 Overview of Previous Production Concepts

Extensive engineering studies were also carried out on various Beaufort Sea production systems in the 1970s and 1980s, as part of industry's activities. These studies included development system components such as offshore structures to resist ice, offshore pipelines to cope with the effects of ice scour and permafrost, and marine systems for different offshore construction activities and for the transportation of oil by tankers. As noted earlier, the plans that were being developed for oil production from the Beaufort Sea were quite well advanced at the time, but were shelved in the late 1980s, due to low oil prices and poor project economics.

Figure 4.17: Views of the Kulluk and support icebreakers operating in managed ice conditions.

Some of the oil development approaches that were being pursued, and discussed in public venues at the time, are briefly highlighted as follows:

- A Dome concept, involving the use of massive dredged Arctic Production and Loading Atoll (APLA) and highly ice-capable tanker fleet, for year round oil production and export from the Beaufort Sea's transition zone. The APLA structure was an extension of artificial island technology and, in principle, was designed to withstand all extreme ice features (i.e.: multi-year hummock fields and ice islands). It had a large amount of oil storage and would be configured in a horse-shoe shape, to allow tanker access and loading within its protected central portion. This and other development concepts, from the early 1980s time frame, are described in the Beaufort Sea EIS (1982).

- Gulf Canada's Amauligak development concept, which involved the use of a large GBS drilling and production platform, a sub-sea oil pipeline to North Point, and an onshore pipeline to the south, also for year round oil production from the transition zone area. Two alternative structures were considered at the time (in the mid 1980s), the CRI which was an extension of the technology used in the Tarsuit CRI, and the MSOB (monolithic structure on a berm) which was an extension of Molikpaq caisson technology.

- Gulf's lesser scale oil development project for Amauligak, which involved the use of the Molikpaq caisson with some onboard oil storage, and ice capable tankers offloading oil and exporting it around Point Barrow on a limited seasonal basis.

The Amauligak-type development approaches, and another scheme that involves the production of near-shore oil reserves (in the landfast ice zone) using of a low cost structure and a small diameter pipeline to shore, and then down to Norman Wells, have also been reviewed in some of the R&D Planning studies conducted by PERD in the 1990s (e.g.: Croasdale, 1994).

5.0 Previous Evaluations of Beaufort R&D Needs

5.1 General

A number of evaluations of Beaufort R&D needs have been carried out in the past, some focusing on ice-related problems, and others being broader in scope. Some of the initial assessments were produced by the oil industry in the 1970s and 1980s, with the range of ice-related projects undertaken within industry being a direct reflection of their needs. More recent evaluations of R&D requirements for Canada's frontiers were also conducted by PERD during the 1990s. A few comments about these initiatives are provided here, as additional background, starting as far back as the R&D work undertaken by the APOA several decades ago. It is interesting to note that most of the ice-related R&D themes outlined in these earlier evaluations have not changed significantly over the years, although progress has been made in many of the key topic areas.

5.2 The APOA

When offshore exploration activities were about to be undertaken in the Canadian Beaufort Sea, a significant R&D program was initiated by the Canadian oil industry, often with the collaboration of government agencies and scientists. Some of the basic research that was first conducted was directed towards environmental conditions in the near-shore waters of the Beaufort, ice mechanics and seafloor conditions. The thrust of this initial R&D work, which began as early as 1969, was to develop appropriate design criteria for the structures being considered for exploratory drilling and future production operations in the shallow waters of the Beaufort Sea.

At the time, the industry players that were interested in the Beaufort Sea (and High Arctic area) recognized the need for collaboration and formed the Arctic Petroleum Operators Association (APOA) in 1970, specifically to conduct joint industry research projects (JIPs). Over the course of its fifteen year existence, the APOA carried out well over 200 projects that were related to various Beaufort Sea problems, ranging from ice conditions, to ice loads, to various structure designs and operations in ice. The nature of the APOA and the range of JIPs that it carried out are described in Hnatiuk & Wright (1981), with listings of APOA projects (and other industry ice studies) updated in Wright (1993). One major undertaken under the auspices of the APOA was the Joint Industry-Government Beaufort Sea Environmental Project, conducted in 1974 and 1975. It involved a wide range of topic areas, from physical environmental conditions in the Beaufort, through the region's biological regime, to oil spill behavior and countermeasures in ice. This work was a precursor to Dome's entry into the deeper waters of the Beaufort Sea with their drill-ship fleet, and part of the approval process required to allow these deeper water drilling operations.

The APOA (and its parallel AOGA group in Alaska) was a very good vehicle to foster cooperation between oil companies, to consider various R&D needs, and to conduct ice-related and other R&D projects on a jointly funded basis. The emphasis of the R&D that was carried out by the APOA was largely on the development of knowledge that could be applied to achieve safe and sound operations in the Beaufort Sea (and High Arctic). The research collaboration that was achieved by the APOA is highlighted here, since it is a prime example of how industry (and government) has successfully conducted joint research in the past, when there was a common need.

5.3 The ESRF

In the mid 1980s, as industry's interest in the Beaufort Sea and Arctic Islands regions began to wane, the APOA was absorbed into the Canadian Petroleum Association's Frontier Division (now CAPP), where its R&D focus was quickly lost. This was partly the result of the creation of the Environmental Studies Research Fund (ESRF) that was supported by an industry levy. The basic intent of the ESRF was to more equitably spread R&D costs relating to various environmental and social matters over all acreage holders in various frontier regions of Canada.

Although some ice-related R&D work was carried out by the ESRF over the next few years, it was less focused on satisfying engineering needs than most APOA projects had been. Moreover, social and biophysical issue areas began to occupy more of the ESRF's annual budget. In this regard, equal government and industry responsibility in determining how best to allocate the funding that was provided to ESRF was not always smooth, since different individuals (and their departments) had different interests and priorities.

In the late 1980s, small working groups that were comprised of a few industry and government representative were formed to discuss and direct some of the ESRF's expenditures in topic areas such as ice scour, physical environmental matters (wind, wave, iceberg and sea ice issues), and oil spill countermeasures. These groups spawned a number of good ESRF projects related to these types of physical environmental considerations in the late 1980s and early 1990s. However, much of the work was directed towards East Coast problems area, since the Beaufort Sea and studies relating to it were loosing priority at the time.

It is noteworthy that one ESRF project dealing with the collection and assessment of extreme multi-year ice feature data in the Beaufort Sea was undertaken in 1992. This study can be viewed as a precedent for the type of ice-related work that could be carried out under the auspices of ESRF in the future.

Over the past few years, some ESRF funded work has been done in the Beaufort. However, this work has been focused on biological issues, and has dealt with various marine mammal and fish considerations. Discussions about ESRF projects and funding were held with CAPP as part of this ice-related R&D assessment. The feedback received from CAPP suggested that sea ice and other physical environmental studies for the Beaufort Sea could be reintroduced to the ESRF, as long as there was industry support to see them carried out under this venue. In this regard, much of the iceberg related work done through ESRF for the Grand Banks area was cited as a clear parallel.

The question of using ESRF funding for ice-related studies in the Beaufort Sea was also raised with some of the oil company representatives that were interviewed as part of this work. Some of them felt that ESRF funding should not be overlooked as an option to promote necessary ice-related R&D work in the Beaufort Sea. However, they pointed out that an industry "champion" would likely be needed to redirect ESRF funds in this manner. They also noted that the current distribution of Beaufort acreage holders, and the resultant ESRF levies on each one, would likely be an area of concern, because the level of interest within many companies who have retained in their share of lands in the region has been largely dormant for some time.

5.4 1982 Beaufort Sea EIS

In the very early 1980s, Dome, Esso and Gulf prepared an environmental impact statement (EIS) that was related to potential hydrocarbon developments in the Mackenzie Delta and offshore Beaufort Sea. The intent of this EIS was to review various development plans for both the onshore and offshore parts of the region, and to assess the potential impacts of types of developments that were being considered at the time. This work was undertaken with a view to clearing the way for timely development project approvals, as the time frames of these projects were viewed as quickly approaching, particularly by Dome Petroleum.

As part of this process, all of the R&D needs that were considered to be important at the time were itemized within the EIS. The key ice issue areas, and the ice-related R&D thrusts that were cited as being important in the 1982 EIS report series, are simply listed as follows.

- measurements of ice loads and interactions with offshore platforms
- the effect of offshore structures on the near-shore ice regime
- the strength of multi-year ice, and multi-year ice load levels
- driving forces on extreme ice features within pack ice
- ice scour on underwater berms
- protection of offshore structures by ice rubble
- growth and decay of ice rubble around offshore structures
- optimal island and structure geometries for ice (and waves)
- refinement of ice occurrence statistics and ice geometries (cited as a joint government and industry responsibility)
- methods for breaking extreme ice features
- ice conditions along tanker export routes (also cited as a joint government and industry responsibility)
- ice scour on the seafloor, and sub-sea pipeline design
- remote sensing of ice (detection, tracking, forecasting, etc.)
- oil spill countermeasures in ice area
- tanker design and transit operations in ice

Most of these topic areas were pursued by various industry and government R&D programs over the early to late 1980s, and to a lesser extent over the past 15 years. However, some of the basic considerations that can be associated with them have never been fully resolved.

5.5 Industry Input to PERD in the Late 1980s

During the mid to late 1980s, industry was asked to provide representatives to more actively input into the R&D activities that were being supported by PERD. These representatives developed a framework for R&D priorities, on the basis on development scenarios for Canada’s frontier areas. The R&D priorities that were identified for oil and gas activities in the Beaufort Sea over this time period are summarized in Table 4.1. The main R&D themes in this table are generally consistent with those identified in the previous Beaufort EIS, and also in subsequent assessments of R&D needs. An outgrowth of industry’s input at the time was the creation of a PERD Ice Structure Interaction Committee (ISIAC), to provide a stronger focus on ice and ice load problem areas.

	Fixed Platforms	Offshore Pipelines	Tankers	Exploration
Ice/Structure Interaction	H	H	L	M/H
Ice Detection, Forecasting and Management	L(1)	L	H(2)	M
Engineering and Design	M/H(3)	H	M	M/H
Seafloor Issues	H	H	N/A	L
Permafrost	H	H	N/A	L
Wave and Current Criteria	M(4)	L	L	L
Wave and Weather Forecasting	L	N/A	L	L
Safety and Evacuation	H	N/A	L	L
Oil Spills in Ice-Covered Waters	H	H	H	H

Notes: H = high, M = medium, L = low and N/A means not applicable
1 – keeping an inventory of ice islands important for impact risk evaluations
2 – detection is the important aspect for tanker operations
3 - priority related to the development of standards (CSA S-471 at the time)
4 – storm wave erosion of hybrid (sand berm and structure) platforms in the key issue here

Table 4.1: CPA priorities related to the Beaufort Sea developments (from 1992).

This table contains entries for different components of an offshore Beaufort development system, with relative priorities identified for various ice, met-ocean, geotechnical, and emergency response topic areas. Most of these topic areas are self explanatory, with the possible exception of seafloor issues, which includes factors such as seafloor scouring by ice, shallow gas, and weak foundation conditions. Although a number of environmental impact issues were also addressed in a similar format, they are not included here. It is noteworthy that the potential effects of climate change were not foreseen as a particularly high priority consideration at the time, at least within industry.

5.6 More Recent PERD Assessments of R&D Needs

Several PERD funded assessments of R&D needs were carried out in the 1990s, to obtain more input about key issue areas for potential hydrocarbon projects in Canada's frontiers, ones in which more knowledge and progress could enhance the likelihood of future developments. The overall intent of these studies was to obtain guidance as to how PERD expenditures could best be focused to make a difference and in turn, enhance the attractiveness of oil and gas opportunities that were available in Canada's offshore regions. Some of the main aspects of these studies that are relevant to ice-related R&D requirements in the Beaufort Sea are highlighted as follows.

Wright & Masterson (1992)

In 1992, the PERD Ice/Structure Interaction Committee sponsored a study entitled "*A Review and Assessment of PERD and Other Ice/Structure Interaction Work*". This was a detailed and specific assessment of ice interaction and ice loading issues for fixed and floating platforms on the Grand Banks, and bottom founded structures in the Beaufort Sea. Although it was carried out in the context of the development scenarios considered to be most probable at the time, the scope of the study did not include topic areas like ice scour and sub-sea pipelines, in-ice tanker loading and export systems, EER and oil spill issues, and so forth.

Ice-Related R&D Requirements for Beaufort Sea Production Systems

The Beaufort Sea component of this 1992 assessment focused on the type of information that was required to develop appropriate design ice load criteria for fixed structures in the intermediate water depths of the Beaufort, in transition zone ice conditions. The ice-related R&D requirements that were identified, discussed and prioritized in the study are listed as follows:

- a better knowledge base upon which global ice loads calculations for extreme multi-year ice features interactions can be based, including all of the ingredients that are needed to reliably compute global design ice load levels on a fixed structure, such as:

  - ice failure pressures and scale effects in very thick multi-year ice features
  - the ice failure modes that are actually associated with extreme ice feature interactions in full scale (e.g.: crushing, out of plane ice failures, ice floe fracture and splitting, frozen-in pack ice driving forces, etc.)
  - global ice moment aspects due to off-center impacts and non-uniform extreme ice feature geometries, with particular reference to elongated structures
  - ice clearance aspects during extreme ice feature interactions with wide (100m or so) deep draft (20m or so) structures, including the potential for ground ice rubble formation during the interaction process (and potentially affect peak ice load levels)
  - the basic characteristics (thicknesses, horizontal extents, through-ice strengths, etc.) and occurrence statistics of extreme ice features (e.g.: multi-year hummock fields), which are a fundamental input for design ice load calculations

- an assessment of the relative advantages and disadvantages of sloped versus vertically-sided structures, relative to expected global design loads caused by extreme ice features, and the ability of these structural forms to resist the "full" extreme ice feature interaction process, including the potential for grounded ice rubble formations that may occur

- local to semi-global ice loads on structures from very thick multi-year ice features, over scales of $10m^2$ to $100\ m^2$

- an improved understanding of the causes of dynamic ice loads from extreme ice features, and an assessment of the key sensitivities of dynamic ice loading events as a function of ice characteristics, movements and structural form

- a review of existing data on grounded ice rubble formations around offshore structures in moving pack ice, and their effects on mitigating ice load levels, including:

  - the water depths in which grounded ice rubble fields are expected to occur, their probable horizontal extent and characteristics, and their patterns and timing of decay
  - the nature of ice interactions with grounded ice rubble fields, including both normal and extreme (multi-year ice) events
  - ice load transmission though grounded ice rubble formations
  - better definition of the role that grounded ice rubble may play in the context of its use as a structural element in hybrid structures
  - an assessment of how spray ice could best be used to enhance the stability and benefits of grounded ice rubble around fixed offshore structures, as well as a continuation of efforts to use spray ice to construct low cost exploration structures and extend its longevity

- ongoing work with probabilistic ice load models, particularly for extreme multi-year ice interactions, and the exercising of these models to identify key areas of uncertainty and in turn, priority needs for future work

- an assessment of the probable effectiveness of any sub-sea berms that may built under or around offshore structures, to mitigate the loads from extreme multi-year ice features

- a review of ice ride-up and ice pile-up issues and information, in relation to the freeboard requirements for fixed offshore structures

- the development of consistent and agreed-to semi-empirical methodologies to determine first and multi-year design ice loads on various offshore structures

Some basic themes were also outlined in this 1992 ice/structure interaction R&D assessment that formed an underlying part of what was recommended. These themes included:

- the creation of an ice/structure interaction center, preferably at NRC/CHC, which would house relevant information that had been acquired by industry and others in the past, data that was in jeopardy of being "buried and eventually lost" with the downturn and attrition of people being seen at the time
- consolidation of the (existing) full scale ice interaction and load information that had been gathered during previous Beaufort Sea structure deployments and R&D efforts
- treating the definition of ice-related R&D needs on a scenario basis, guided by key areas of uncertainty in which better understandings could make both a technical and economic difference for future industry development projects
- the formation of a small working group (perhaps as an ad-hoc part of ISIAC) composed of several ISIAC and interested industry members, to assess ongoing ice R&D needs for key Beaufort scenarios, promote ongoing ice R&D initiatives, and review their results and effectiveness in the context of improving the knowledge base for and attractiveness of the key scenarios

Croasdale & McDougall (1994)

PERD carried out a subsequent evaluation of R&D needs in 1994, but its scope was much broader than the 1992 ice/structure interaction requirements study. This work was sponsored by OERD and was intended to provide directions, priorities and economic justifications for PERD R&D expenditures, in relation to potential hydrocarbon developments in Canada's frontier regions. This was the era of low oil and gas prices, a low level of industry interest in most of Canada's frontiers, and the "size of the prize" approach that K. Croasdale was promoting, as a basis for defining how PERD's frontier R&D expenditures could best be focused.

This work included economic evaluations of different development concepts for various offshore regions in Canada, and the sensitivity of the resultant project economics to "technological uplifts" that could be accomplished through focused R&D. Plausible Beaufort scenarios that were identified involved small and moderately sized oil field developments, with either a seasonal or year round tanker export system, or a small pipeline to Norman Wells.

Ice-Related R&D Requirements for Beaufort Sea Production Systems

The ice-related priorities that were identified for Beaufort development schemes considered in this study, and justified by the economics that were run, are highlighted as follows:

- Offshore Structures

- develop more reliable and less conservative ice loads
- develop ice load protection and mitigation techniques for extreme ice events
- develop methods to mitigate adverse dynamic ice loads
- develop optimized shape for structures to contend with ice and wave effects
- adaptation of existing caissons (assess risks and appropriate design ice load levels within a probabilistic framework, and then focus on uncertainties)
- investigate spray ice barriers to protect structures against ice and waves
- conduct a study on extreme ice features and their management
- develop industry consensus on ice loads on production platforms

- Offshore Pipelines

- faster construction techniques
- use spray ice causeways to build off the ice
- assess burial depth versus risk (minimize trenching)
- optimize trenching using ploughs, dredges, etc.

- Tanker Export

- tanker transit and risk assessment (based on world wide experience)
- innovative ideas for offshore storage
- optimization of tanker size and numbers for various production scenarios
- field demonstration and data gathering using ice capable vessels (January to April period)
- knowledge of ridge fields and ice pressure along ship transit routes, and their influence on transit times
- assessment of environmental protection systems including double hulls and oil spill response in ice
- ice impact loads during tanker transits, particularly in multi-year ice
- integration and assessment of work done to date on vessel design, materials, corrosion and ice loads on machinery
- development of fuel efficient tanker designs
- design of offloading systems in ice
- ice management around loading terminal/structures

Croasdale and others (1999)

In 1999, OERD sponsored another R&D requirements study to better focus and justify its R&D expenditures, but in this case, across the full hydrocarbon energy sector in Canada, not only in the frontiers. Again, this work was carried out by K. Croasdale (and others), and was founded on the size-of-the-prize theme. Although the study was primarily oriented towards technical needs, it also recognized the importance of green house gas issues, which had become topical by that time.

The Beaufort Sea component of this R&D needs assessment work was relatively small. However, a number of ice-related R&D requirements were reaffirmed for the Beaufort, with the priority items that were cited in the study including:

- improved sea ice statistics
- methods for prediction of ice loads due to seasonal sea ice and extreme ice features
- novel low cost structure designs for extreme ice loads and difficult foundation conditions
- improved seafloor ice scour statistics
- methods of protection of sea floor facilities and pipelines from ice keels
- technology and knowledge to improve the acceptability of Arctic marine transportation
- oil spills in ice

5.7 PERD Responsiveness

It is important to note that PERD has been very responsive in terms of addressing some of these ice-related R&D needs. In the regard, the leadership of G. Timco of NRC-CHC, who has chaired the PERD Ice/Structure Interaction Committee for some time, and S. Blasco of GSC-AGC, who has pursued various seafloor ice scour and other geo-hazard issues, should be acknowledged. The ongoing work of H. Melling of DFO-IOS in conducting studies related to Beaufort ice conditions over the past fifteen years is also noteworthy.

Readers are encouraged to visit the NRC-CHC, GSC-AGC and DFO-IOS websites to review the range of studies that have been carried out in key ice-related issue areas. Although Beaufort ice topic areas have not been overlooked in PERD's frontier R&D program over the past 15 years or so, more effort has been focused on Grand Banks and Scotian Shelf problems over this time period, because of the higher priority status of these hydrocarbon regions within government and industry.

6.0 Discussions with Companies

6.1 Basic Approach

The first part of this study involved meetings and discussions with representatives of various oil companies who have current or past interests in the Beaufort Sea, as well as companies with ice-related experience in other offshore regions of Canada. The objective of these discussions was to review any potential exploration or development plans that companies may have for the Beaufort, to identify the ice-related issues they may be concerned about, and to solicit their thoughts about ice-related R&D needs. As part of these discussions, more general topic areas were also covered, such as likely time-lines for Beaufort Sea activities, possible drilling and production scenarios, and the broader range of impediments that are foreseen for potential oil or gas developments in the region.

At the outset of this work, meetings were held with several oil companies in Calgary, with G. Timco and A. Barker of NRC-CHC, and B. Wright, being in attendance. As the study progressed, B. Wright had various follow-up discussions and meetings with these and other companies, along with stakeholders from the government and public sectors, and particular individuals with relevant expertise. A listing of the groups and individuals that were interviewed is given in Table 6.1.

To provide some focus for these discussions, a number of the broad topic areas were identified. They included many of the main building blocks for possible Beaufort Sea development project and are outlined as follows.

- fixed offshore structures
- floating vessel station-keeping in ice
- seafloor facilities and pipelines
- marine export systems
- logistics support systems
- exploratory drilling and seismic
- physical environmental considerations
- oil spill and EER considerations

An attempt was also made to conduct the discussions in the context of several different scenarios, which included:

- gas developments in shallow near-shore waters (to 20m, in landfast ice)
- oil developments in shallow near-shore waters (to 20m, in landfast ice)

- oil developments in intermediate water depths (20m to 80m, or more, in moving pack ice)
- gas developments in intermediate water depths (20m to 80m, or more, in moving pack ice)

- exploration and development in deeper waters (100m or more, near or in the polar pack)

Despite efforts to structure the R&D needs discussions into these topic areas and scenarios, the conversations quickly became broader ranging and less formal, for the following key reasons:

- None of the companies had any definitive plans for future activities in the Beaufort, and they were just starting to consider potential opportunities in the area. The only exceptions were Devon, who will be drilling in the Canadian Beaufort Sea this winter, and Shell, who have just acquired new leases in the Alaskan Beaufort and Chukchi Seas.

- The thoughts received about individual scenarios, which suggested that available reserves (either oil or gas) would most likely be linked together to "hubs" by sub-sea production and pipeline systems, and developed in a temporally staged regional manner.

Groups & Individuals Interviewed		**Venue for Discussion**	
	Representatives	***In Meetings***	***By Phone***
Oil & Gas Companies			
BP	D. Blanchet		X
	H. Vrielink		X
Chevron Texaco	R. Dahlman	X	
	R. Kerr	X	
	T. Moore	X	
	B. Scott*	X	
Conoco Phillips	D. Seidlitz	X	
	M. Rendle		X
Devon Canada	B. Livingstone	X	
	B. Scott*	X	
Encana	S. Christiansen		X
Exxon Mobil	W. Spring		X
	J. Poplin		X
Shell	M. Hansen		X
	A. Reece	X	
	C. Shaw	X	
CAPP	I. Scott		X
Government Departments			
NEB	B. Dixit		X
INAC	T. Baker		X
NRC-CHC	G. Timco	X	
	B. Frederking	X	
GSC – AGC	S. Blasco		X
DFO – IOS	H. Melling		
Others			
	D. Masterson	X	
	K. Croasdale		X
	R. Browne		X
	S. Potter		X
* B. Scott moved from Devon to Chevron Texaco over the course of this study			

Table 6.1: Groups and individuals interviewed as part of this study.

6.2 Initial Responses on Ice-Related R&D Needs

The initial responses that industry provided about their ice-related R&D requirements were not dissimilar to those identified in previous evaluations, which were outlined in Section 5. Industry's most recent responses about priority needs for improved ice-related information, as determined by this study, are briefly itemized by topic area as follows.

fixed offshore structures

- design ice loads from extreme ice features (i.e.: multi-year ice)
- ice rubble formation around offshore structures
- effects of ice rubble in mitigating the potential for high ice loads
- innovative low cost structures, including the use of spray ice

floating vessel station-keeping in ice

- ice loads on floating vessels station-keeping in pack ice (moored and/or DP)
- the effects of ice management support in terms of reducing ice load levels
- the number and characteristics of ice management vessels required

seafloor facilities and pipelines

- ice scouring, sub-scour deformation and limiting keel strengths
- sub-sea pipeline design and pipe wall thicknesses
- design issues ranging from pre-drilled keeper wells to sub-sea production systems

marine export systems

- tanker loading systems and station-keeping in pack ice
- ice management support requirements
- tanker designs and in-ice transit performance
- multi-year ice impact loads and hull strength
- optimum transit routing and old ice avoidance

exploratory drilling and seismic

- exploratory drilling, particularly floating vessels and ice management needs for extended season drilling operations in the intermediate to deeper water depth ranges
- need for seismic methods in deep ice-covered waters, and in very shallow water areas

physical environmental considerations

- potential effects of climate change on ice conditions (both normal and extreme)
- improved relief well drilling capability
- oil spill countermeasures and clean-up
- dredging concerns (versus ice scour and river sediment "disturbances")

other considerations

- adequacy of escape, evacuation and rescue systems in various ice situations
- marine systems for construction and re-supply
- ice capable support vessels, and their availability

Although the discussions focused on ice-related R&D needs, other key items were also raised as a by-product of the discussions. In this regard, the companies noted that engineering issues would not likely be the main impediment to higher levels of exploration and future production activities in the Beaufort, given the assumption of adequate oil or gas reserves, a go-ahead of the northern gas pipeline (for gas developments), and reasonable project economics. Instead, socio-economic and environmental impact concerns are foreseen as being the major potential road blocks to future hydrocarbon developments in the area. Notwithstanding these broader concerns, various cost and technical do-ability aspects remain of high interest to companies that are now assessing potential oil and gas project opportunities in the Beaufort Sea.

6.3 Further Comments on Ice-Related R&D Needs

It is noteworthy that most of the companies identified the same types of ice-related issues as being of importance. Clearly, there were some differences in emphasis, depending upon whether oil or gas projects were under consideration, and the water depths in which reserves may be located.

After reflecting on the initial industry input about R&D requirements, follow-up meetings and discussions were held with some of the oil companies, along with other stakeholders and key ice experts. The intent of this second go-around was to confirm the basis for various thoughts that had been passed along, to discuss this input further, and to get some feel for how various companies and groups would like to see ice-related R&D work fostered and funded in the future, along with related priorities. Some of the main messages that were affirmed by oil companies and others in this second part of the work are summarized as follows, again by topic area.

6.3.1 Fixed Offshore Structures

- the ice-related knowledge that is required for the design of structures in the Beaufort Sea's shallow water areas is considered to be fairly well in hand, and largely proven in first year ice conditions
- multi-year ice interactions and loads are not viewed as a critical design issue for structures in shallow waters, but a potential increase in the severity of the Beaufort's wave climate due to climate change is of some interest
- the influence of grounded rubble and the use of spray ice is also a topic area of interest, but is seen more as an enhancement that may lead to lower cost structures, as opposed to a determining factor regarding their economic feasibility
- the use of spray ice is a topic of interest on its own, as an option for the creation of low cost exploration platforms and for relief well drilling, with issues including the maximum water depths in which ice pads can be built and how to extend the lifetime of spray ice pads into (or through) the open water season

- the question of global ice loads on fixed structures that may be exposed to thick multi-year ice floes is generally recognized as a topic area with much more uncertainty, and one of considerably higher importance for the design of production platforms that are intended for use in the intermediate and deeper waters of the Beaufort Sea
- this includes multi-year ice action on both bare structures and ones that are surrounded by grounded ice rubble, and the ability of ice rubble to mitigate extreme multi-year ice loads
- the need for improved information on multi-year ice feature thicknesses, including multi-year hummock fields and their impact frequencies, has been appropriately cited by some as a fundamentally important input for extreme design ice load calculations
- the issue of the relative benefits of sloped versus vertically sided structures in terms of their ability to withstand extreme ice features interactions also remains
- in addition, questions regarding the potential for ice island interactions with structures has not been forgotten by some, particularly in light of the of the Ward Hunt ice shelf break-out that was widely reported by the media several years ago, and was largely attributed to the effects of global climate change at the time
- the issue of multi-year ice action and loads on structures is also of interest for other areas of the world, such as the Alaskan Beaufort, Chukchi and northern Barents Sea areas

6.3.2 Floating Vessel Station-Keeping in Ice

- global ice load levels on floating vessels of various shapes and sizes, moored and/or DP, and the ability of these vessels to station-keep in moving pack ice conditions is an area of high interest to companies for the Beaufort (exploration systems, tanker loading, etc.), and for exploration and development operations in many other ice-infested areas of the world (e.g.: the offshore Sakhalin region, the Barents and Pechora Seas, etc.)
- the effect of ice management support in terms of reducing ice load levels and enhancing vessel station-keeping operations in ice is also a key area of interest
- what type of ice management vessels are required (e.g.: necessary levels of strengthening and powering) is another key question, along with the number of ice management vessels that may be needed to provide effective support (and their availability)

6.3.3 Seafloor Facilities & Pipelines

- it is generally recognized that any seafloor facilities and sub-sea pipelines in the Beaufort Sea will be susceptible to the action from deep ice keels and ice scouring,, in the shallow to intermediate water depths of the area
- it was also acknowledge that GSC-AGC had been doing a good job of gathering basic data about ice scour depths and frequencies in the Beaufort Sea, and should be encouraged to continue this work, since it is a fundamental input for seafloor facilities designs
- however, the questions of ice keel strengths and ice/seafloor/pipeline interaction behaviors (including sub-scour deformation) remain, and are viewed as areas of uncertainty
- possible approaches to engineer some sub-sea facilities to withstand ice scouring effects is also of some interest, but need better keel strength and interaction behavior knowledge
- the avoidance of ice scouring effects through trenching, the use of glory holes and so forth was cited as the preferred approach to deal with this constraint by many companies

6.3.4 Marine Export Systems

- the technology that is required to design and operate tankers for oil (or gas) export from the Beaufort Sea is generally considered to be in hand
- however, in-ice tanker loading systems and their effectiveness is an area of interest for the Beaufort Sea, and also for many other areas of the world
- multi-year ice detection and avoidance technology is of considerable interest in relation to tanker transits to and from the Beaufort Sea, but is a topic area that is being handled by other government programs (Timco et al, 2005)
- the question of ice pressure occurrences and severities along the Alaskan transit route in winter is another area of uncertainty, and is an important tanker transit efficiency issue
- the perception of in-ice tanker transit being dangerous is seen a more critical issue area, but is felt to be aligned with deficiencies in oil spill clean-up technologies rather than any design or performance limits with tankers themselves

6.3.5 Exploratory Drilling & Seismic

- although exploratory drilling systems and methods for seismic data collection lie outside of the Beaufort development focus of this R&D needs assessment work, they have been raised as important considerations by a number of companies
- with regard to exploratory drilling operations, one of the key questions is how effective can vessels like the Kulluk or drill-ships actually be in the intermediate to deeper waters of the Beaufort Sea, and how can their drilling seasons be extended
- this issue involves many of the ice load and ice management issues that were highlighted in Section 6.3.2 above
- similarly, the question of low cost exploration approaches for the shallow to intermediate water depths of the Beaufort Sea is also of interest
- some interest was also expressed in relation to the possibility of seismic operations in the deep water areas of the Beaufort Sea, where the presence of pack ice is persistent over both the summer and winter seasons
- a similar item was raised in relation to carrying out seismic work the very shallow waters of the Beaufort Sea (< 6m) that are open in summer, but this is not an ice-related problem area

6.3.6 Physical Environmental Considerations

- the potential engineering implications of climate change on the Beaufort Sea's ice climate is an obvious issue area that was raised, one that will likely be ongoing
- in industry, it is generally felt that a potentially thinning ice cover will be cited as a means of directing any on-ice activities (bearing capacity problems) to be more conservatively planned, but will not be accommodated in terms of the potential relaxation of ice loading design criteria (e.g.: multi-year ice thicknesses)
- most groups and individuals felt that this is an important area to address
- the question of less ice coverage and potentially larger storm wave events is an associated topic area that is also viewed as being important

6.3.7 Other Considerations

- the oil spill and EER topic areas are recognized as being of high importance in practical, regulatory and public perception terms
- the ability to predict oil spill movements in the Beaufort's ice environment is considered to be reasonably well in hand, but questions about its behavior and how best to clean it up are viewed as being considerably less certain
- efforts to improve knowledge in the oil spill topic area have been underway for some time, for example, a workshop to discuss needed oil spill R&D is being held in Halifax later this fall (under the sponsorship of Alaska's MMS)
- EER methods are also seen as a key topic area, but are considered to be well handled by recent ISO standard initiatives, the work of an "ad-hoc EER group that has been underway for the past several years, and some of the studies that have been undertaken by ISIAC

6.3.8 Additional Comments

Despite this listing of ice-related R&D needs, a number of other important comments were also offered as a means of providing some context. They are briefly highlighted as follows:

- There is an important need to manage current expectations about potentially high levels of offshore activity in the Beaufort Sea, at least in the short term.

- In this regard, various companies are just beginning to review opportunities and develop plans, ones that will likely evolve over a period of 1 to 5 years, and will be affected by how the northern gas pipeline question plays out.

- How companies carry out ice-related R&D work that is of high priority to them is unclear at present, but some interest in collaborative work and JIP approaches in some technical areas has been expressed as being attractive by many.

- The general theme of "where are we now with particular ice-related areas of knowledge" is topical within many oil companies, and certain questions are of generic importance to companies with interests in various Arctic and sub-Arctic regions of the world.

- Although socio-economic and environmental impact issues are viewed as likely to be of more consequence than technical do-ability and cost aspects for development projects in the Beaufort, the need to resolve any outstanding ice-related technical issues in a timely manner has been identified as a key need, particularly by government groups.

- PERD is well acknowledged as having undertaken relevant and important ice-related R&D work in the past, but it is time for industry to consider playing a stronger role as their interests in various Beaufort Sea oil and gas opportunities progress.

7.0 Summary of Ice-Related R&D Requirements

7.1 Key Ice Issue Areas

Based on the ice-related R&D needs that have been identified by various industry, government and public groups for potential Beaufort developments through this work, and in previous studies, the key areas of interest are quite clear. In this regard, there is no need to belabor the importance of improved ice information in specific topic areas, since they have generally remained consistent over a number of years.

A summary of ice-related R&D requirements that is based on inputs received in this work is given in Figure 7.1. It includes:
:

- an identification of specific ice issues in key topic areas, subdivided into near-shore water depths (the landfast ice zone), intermediate water depths (the transition zone) and deeper water areas (near the polar pack) of the Beaufort Sea

- an assessment of the relative priorities for further work on the specific ice issues that have been identified, expressed as high, medium or low

- an general assessment of the current state of knowledge in these ice issue areas, expressed as poor, fair or good

This summary represents a blend of the thoughts that were obtained from the various groups and individuals interviewed, and the opinions of the author (B. Wright) and his colleagues at NRC-CHC (G. Timco and B. Frederking).

Clearly, the combination of high priority ice issue areas and either poor or fair state of knowledge rankings form the R&D needs with the strongest requirements. Although some of the priorities that are related to ice issues for potential activities in the deeper water areas of the Beaufort are indicated as high, it is important to note that these types of activities will most likely be a long ways off in time. Time-lines on R&D needs for knowledge improvements related to the near-shore and intermediate water depth zones of the Beaufort Sea are shorter, in the range of several years or so. However, most oil companies cannot really comment on probable time-lines for these needs, because they are just beginning to consider opportunities and have no definitive plans at present.

From the information that is summarized in Table 7.1, key areas for ice-related R&D are:

- global loads from multi-year ice, including a better knowledge of thick ice failure modes and extreme ice feature occurrence, floe size and thickness statistics
- grounded ice rubble formation, and ice load transmission through grounded rubble fields
- floating vessel station-keeping in ice, and associated ice management considerations
- ice scoring processes in relation to seafloor facilities and sub-sea pipeline design
- engineering and operational implications of climate change on Beaufort ice conditions
- oil spill countermeasures and clean-up considerations in ice
- escape, evacuation and rescue considerations in ice

	Near-Shore Zone		Intermediate Zone		Deep Zone	
	Priority	*Knowledge*	*Priority*	*Knowledge*	*Priority*	*Knowledge*
Fixed Offshore Structures						
Global loads from FY Ice	H	G	M	G	L	G
Global loads from MY Ice (& thick ice failure modes)	M - H *	F	H	P	H	P
Local & semi-local pressures from FY Ice	H	G	M	G	L	G
Local & semi-local pressures from MY Ice	M - H *	F	H	F	H	F
Ice rubble formation	H	F	L - H **	F - P	L	P
Load reduction from ice rubble	H	P	L - H **	F - P	L	P
Statistics on MY ice population/size/thickness	H	G - F	H	F - P	H	F - P
Sloped versus vertical-sided structure?	M	F	M	F - P	L	F - P
Spray ice technology	H	G	M - H **	G	NA	-
* depends on water depth, and the risk of multi-year ice interactions with a structure						
** depends on design philosophy of getting some protection from grounded ice rubble or spray ice, or otherwise						
Floating Vessel Station-Keeping						
Ice loads on floating vessels (moored and/or DP)	L	G - F	H	G - F	H	P
Ability to station-keep in prevailing ice conditions	L	G	H	G - F	H	F - P
Knowledge of ice management effectiveness	L	G	H	G - F	H	F - P
Vessel requirements for ice management *	L	G	H	G	H	F - P
* includes topic areas like number of vessels, levels of ice-srengthening and powering, utility of azimuth thrusters, etc.						
Seafloor Facilities & Pipelines						
Knowledge of ice scour statistics	H	G	M	G	NA	-
Ice keel strengths - FY & MY ridges	M - H	P	M - H	P	NA	-
Keel scouring processes & sub-scour deformations	H	F - P	M - H	F - P	NA	-
Marine Export Systems						
Tanker design & operation	L	G	H	G	H	F
Tanker station-keeping while loading	L	-	H	F	H	P
Tanker loading systems	L	-	H	F	H	F
MY ice impact loads & hull strength	L	-	H	F - G	H	F - G
MY Ice detection & optimum transit routing	L	-	M	G	M	G
Exploratory Drilling & Seismic						
Drilling system needs for extended season ops	L	G	M	G	M	P
Seismic methods in deep ice-covered waters	-		-		H *	F - P
Seismic methods in very shallow waters	M	P	-		-	
* this is not a short term priority, since there are no plans for deep water exploration in the Beaufort Sea at present						
Environmental Considerations						
Effects of climate change on ice conditions	H	F	H	F	H	F
Improved relief well capability	M	F	M	F	M	F
Dredging concerns	M	F	M	F	L	-
Oil spill countermeasures & clean-up	H	F	H	P	H	P
Other Considerations						
Emergency escape, evacuation & rescue systems	H	G - F	H	F -P	H	P
Marine systems for construction & re-supply	M	G	H	G	H	F - P
Ice-capable support vessel needs & availability	M	G	H	G	H	F - P

Table 7.1: Summary of key ice-related R&D needs for the Beaufort Sea, their relative priorities and the present state of knowledge in each ice issue area. H, M and L mean high, medium and low while G, F and P means good, fair and poor. Note that any potential activities in the deeper waters of the Beaufort are a long way off in time, a factor that is not reflected in most of their relative priorities.

For the purposes of this R&D assessment, a key question is what should be done in these ice topic areas and how, with a view to getting some of the necessary ice-related R&D work initiated, but in a sensibly paced and step-wise manner.

7.2 Resources and Approaches

There are a variety of interested companies, sources of industry and government funding, and methods of approach that could be used to pursue the type of ice-related R&D needs that have been identified above. Clearly, PERD is one of them. However, there are other potential funding or in-kind support sources, including:

- The ESRF, which involves industry funds collected through a prorated acreage-based levy
- Funding (or in-kind) contributions from individual oil companies that may be interested in specific research initiatives for the Beaufort, some of which may be generically applicable to their interests in other ice-covered waters of the world
- Joint Industry Projects that may provide funding from a number of interested companies and government groups
- Possible participation of international institutes and interested groups in the types of ice-related R&D projects that may be carried out (largely) in Canada

One theme that has arisen as part of the discussions this R&D assessment work, particularly with some of the individuals who were involved with associations like the APOA and AOGA in the past, is the importance of communication, cooperation and collaboration. In this regard, thoughts that have been raised range from the possibility of joint R&D projects spearheaded by individual companies to the possibility of an ad-hoc group comprised of interested companies that could discuss and foster necessary ice-related research for the Beaufort, perhaps formed under the umbrella of CAPP. This latter approach would be similar to the ad-hoc EER group that has been operating for some time.

Some of the primary ingredients of an approach that may be most practical at this point in time are outlined below. Here, they are simply offered as some food for thought and further discussion.

- PERD funding for ice-related R&D work (through ISIAC) over the first couple of years of any such initiatives, with some incremental funding (or in-kind) support from interested industry companies
- possible ESRF funding for work in some of the ice data assessment or acquisition issues (e.g.: on extreme multi-year ice feature statistics, which was the subject of an ESRF study in the early 1990s)
- increasing levels of industry funding and/or in-kind support over time, as the plans of different oil companies begin to evolve, to undertake some of the more major ice-related field projects that may be required
- soliciting international participation in ice-related R&D projects that may be of communal concern, either by direct funding or technical (or logistics) support in-kind

7.3 Specific Ice-Related R&D Thrusts

A considerable number of ice-related R&D requirements have been identified over the course of this assessment work. After some reflection, four specific ice-related research thrusts have been defined and are recommended for further consideration. These thrusts are intended to address high priority areas of need where there is either limited information, or where a front-end synthesis of existing data would be both beneficial and timely. They include:

- Multi-year design ice loads on fixed structures
- Ice loads on structures surrounded by grounded ice rubble fields
- Engineering and operational implications of climate change on Beaufort ice conditions
- Ice loads on vessels station-keeping in pack ice

Some of the higher priority topics such as seafloor ice scour processes, oil spill countermeasures and clean-up and EER systems are not included, since they are viewed as being either adequately or best addressed elsewhere, as part of other ongoing efforts.

Flow charts that show the individual components of these suggested ice-related R&D thrusts have been developed and are provided in Figures 7.1 through 7.4. These methodologies incorporate a various issues from Table 7.1 into logic frameworks that are intended to treat overall ice problem areas as a whole. Interrelationships and synergies between some of the components of these four R&D thrusts are also indicated in the figures. For the most part, the flow charts and the individual R&D elements within them are self-explanatory. The lines that are indicated by red represent the demarcation between low to moderate cost "paper" studies and higher cost field projects. The timing that is assumed moves from left to right over a several year period, but is not specified.

A few additional comments about these four ice-related R&D thrusts are given as follows.

7.3.1 Multi-Year Ice Loads on Fixed Structures

- this ice topic area is of high importance for both the Canadian and Alaskan sectors of the Beaufort Sea and the northern parts of the Chukchi Sea, but is of little importance in other areas of the world where only first-year ice is encountered
- there is a very limited amount of full scale experience with multi-year ice action and loads on fixed near vertical structures, which has never been fully synthesized in the context of predicting design ice load levels from extreme multi-year ice features (although some of the data has been assessed from a global and local ice loading perspective in previous PERD and other studies)
- also, there is no full scale experience with ice action and loads from very thick ice feature interactions with sloped structures, although analytic work and model testing has been done in the past

- the first component of the effort that is highlighted in Figure 7.1 is intended to synthesize existing information about extreme multi-year ice loads in the context of both vertical and sloped-sided structures, and to address the question of "where do we stand now ?"
- the cost of this type of effort would likely be in the range of $100,000 or so, and would be of value in terms of documenting existing information in a focused manner (e.g.: for input to the ISO Arctic code development work), even if offshore activities in the Beaufort Sea do not proceed in the future
- the second component of the effort deals with the collection and review of representative imagery of natural structures that are subject to multi-year ice interactions at low cost (in the order of $50,000 or so), such as that provided by the high resolution visual sensors onboard the Quickbird satellites
- this part of the methodology would allow people to begin considering potential full scale data acquisition opportunities regarding multi-year ice interactions and loads, at least until the time opportunities again arise from man-made structure deployments in multi-year ice environments
- one important input to the question of multi-year design ice load levels involves extreme ice feature statistics, which is an interrelated input to this work that could be generated as part of research thrust # 3
- the logical extension of the initial work items in the overall effort involves the type of full scale projects that are indicated on the right-hand side of the suggested methodology
- data acquisition programs on extreme ice feature statistics would likely be in the range of $150,000 to $200,000 or so, while large field projects involving multi-year ice interaction observations and load measurements could be substantially more expensive, in the order of $500,000 or more
- it is felt that an overall efforts along the lines outlined in Figure 7.1 are best administered by ISIAC, and are likely best spearheaded by NRC-CHC

7.3.2 Rubble Formation & Ice Load Transmission through Grounded Rubble Fields

- this topic area is of high interest for fixed structures located in the near-shore waters of the Beaufort, and those that may be designed to benefit from grounded rubble accumulations (and spray ice) by potential load mitigation, in the area's intermediate to deeper waters
- the topic may also be of interest to companies that are involved in regions like the Pechora Sea, and in the shallower waters areas off Sakhalin Island
- the first component of this effort is also a "where are we now" review and synthesis of existing information, which should be doable at a cost $75,000 or so
- a second component of the effort (and follow-ups to it) involve observations of grounded ice rubble and loads that will be acquired around the SDC by Devon this coming winter (and in future years if they have success with and pursue their exploration program)
- Devon has already agreed to provide NRC-CHC with in-kind support to do some field work around the SDC, and to carry out some assessment of the data that Devon acquires within the scope of their drilling activities over the 2005/06 winter period
- one R&D stream shown in Figure 7.3 involves the question of extreme multi-year ice action on grounded rubble around structures, and leads to potentially expensive field work (several hundred thousand dollars or more, that is also related to research thrust # 1)
- this type of work is felt to be best administered by ISIAC, and spearheaded by NRC-CHC

7.3.3 Engineering & Operational Implications of Climate Change on Ice Conditions

- the study components that are outlined in the methodology for this R&D effort (see Figure 7.3) are Beaufort Sea specific, and should be quite clear
- climate change issues are well recognized and will be an important and topical area during regulatory and public reviews of any Beaufort Sea projects that may be undertaken in the future
- an important point to note is that the work suggested in relation to multi-year ice feature thicknesses addresses not only the climate change issue, but is an important input for R&D thrusts # 1 (and to a lesser extent R&D thrust # 2)
- it is felt that ISIAC should administer this effort, with H. Melling of DFO-IOS being responsible for the ice climate science and statistics, and NRC-CHC being responsible for assessing the engineering and operational implications of the resultant information
- the initial stages of this type of effort would likely be in the range of $100,000, with any follow-up field work being somewhat more costly
- one ingredient of the effort involves basic and ongoing ice thickness data acquisition in the Tuktoyaktuk area by the Inuvialuit, to provide quantitative information for the future, an initiative that should cost no more than $10,000 or so per year

7.3.4 Loads on Station-keeping Vessels in Ice

- this is a topic that is of importance to a variety of companies with interests in different ice-covered parts of the world, not only for those considering future activities in the Beaufort Sea
- the various components of the methodology illustrated in Figure 7.4 should be clear, and involve work elements to address questions as to “where are we now ?”, and to document future in-ice vessel station-keeping and ice management operations, as opportunities arise
- the review and synthesis of existing information about ice loads on station-keeping vessels should include Beaufort Sea systems and more recent operations in other areas of the world, such as those now in place or upcoming off Sakhalin Island, in the Pechora Sea and in the Gulf of Bohai, as well as the short term “core drilling program” carried out in the Arctic Ocean (on the Lomonosov Ridge) last summer
- it is not clear how all of the new data about vessel station-keeping and ice management activities could be released and incorporated into this effort, but use of the complete suite of data (or at least know-how) that currently exists is highly desirable
- this is an input area that is also being considered by the ISO Standards technical panel now developing guidelines for floating system designs in ice
- the cost of an initial review and synthesis of information about loads on station-keeping vessels in ice, and ice management support requirements, would likely be in the range of $100,000 to $150,000
- any follow-up projects to document ice loads on floating vessels and ice management during full scale operations would probably be offered as JIPs, at similar or higher cost levels
- again, this is an R&D topic area that ISIAC has administered in the past, and is probably best spearheaded by NRC-CHC, at least in the short term

R&D Thrust # 1

Multi-Year Design Ice Loads on Fixed Structures

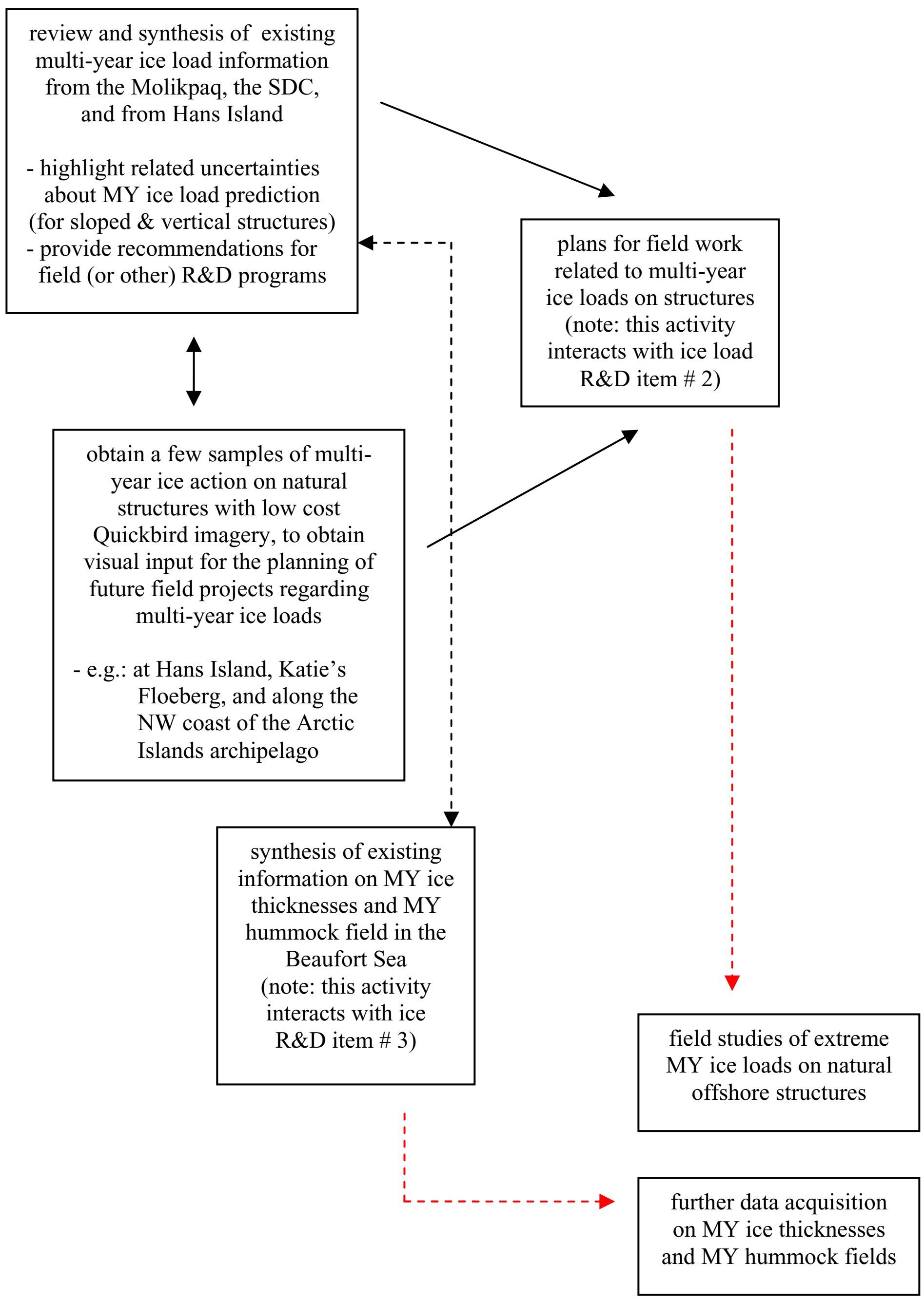

Figure 7.1:

R&D Thrust # 2

Ice Loads on Structures Surrounded by Grounded Ice Rubble Fields

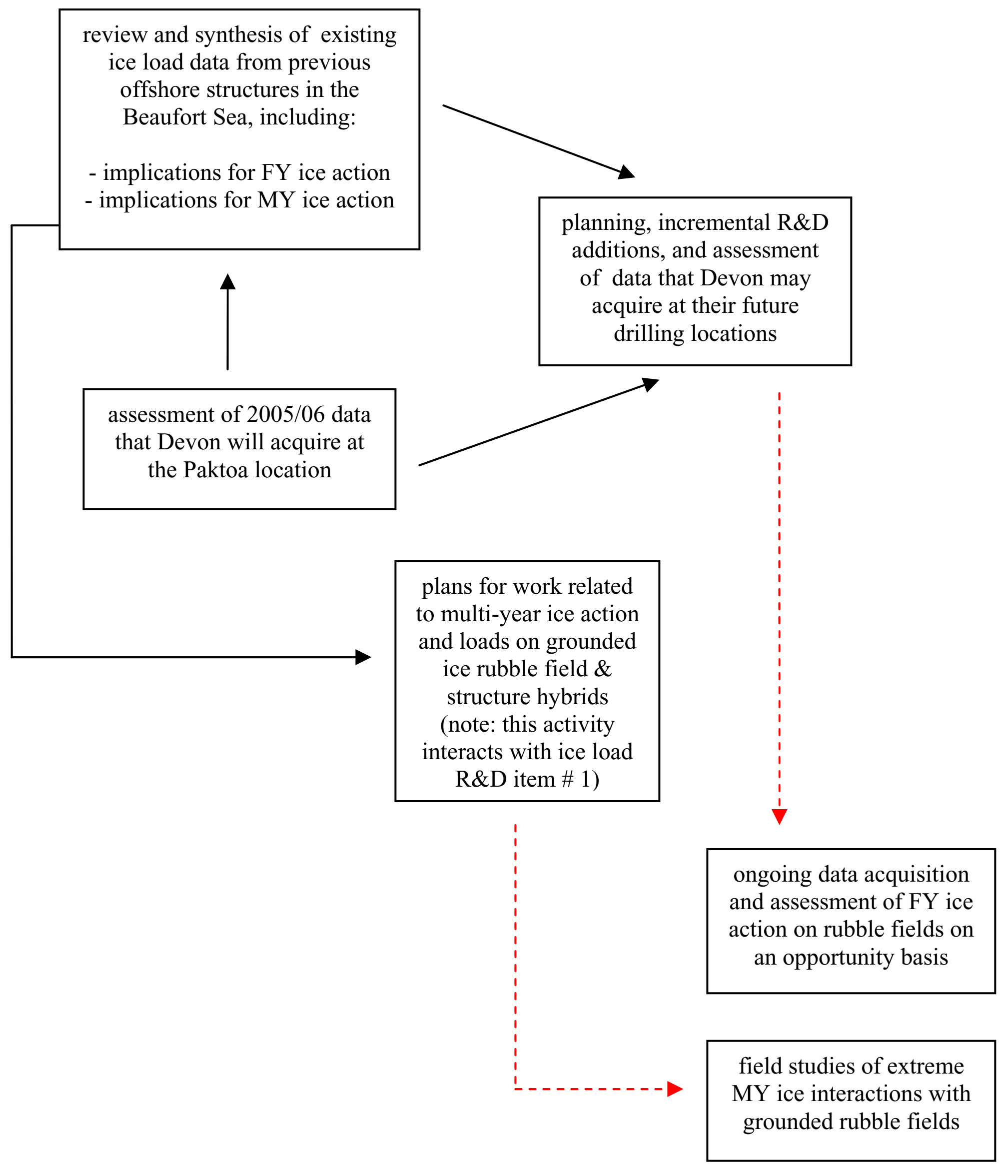

Figure 7.2:

R&D Thrust # 3

Engineering and Operational Implications of Climate Change on Beaufort Sea Ice Conditions

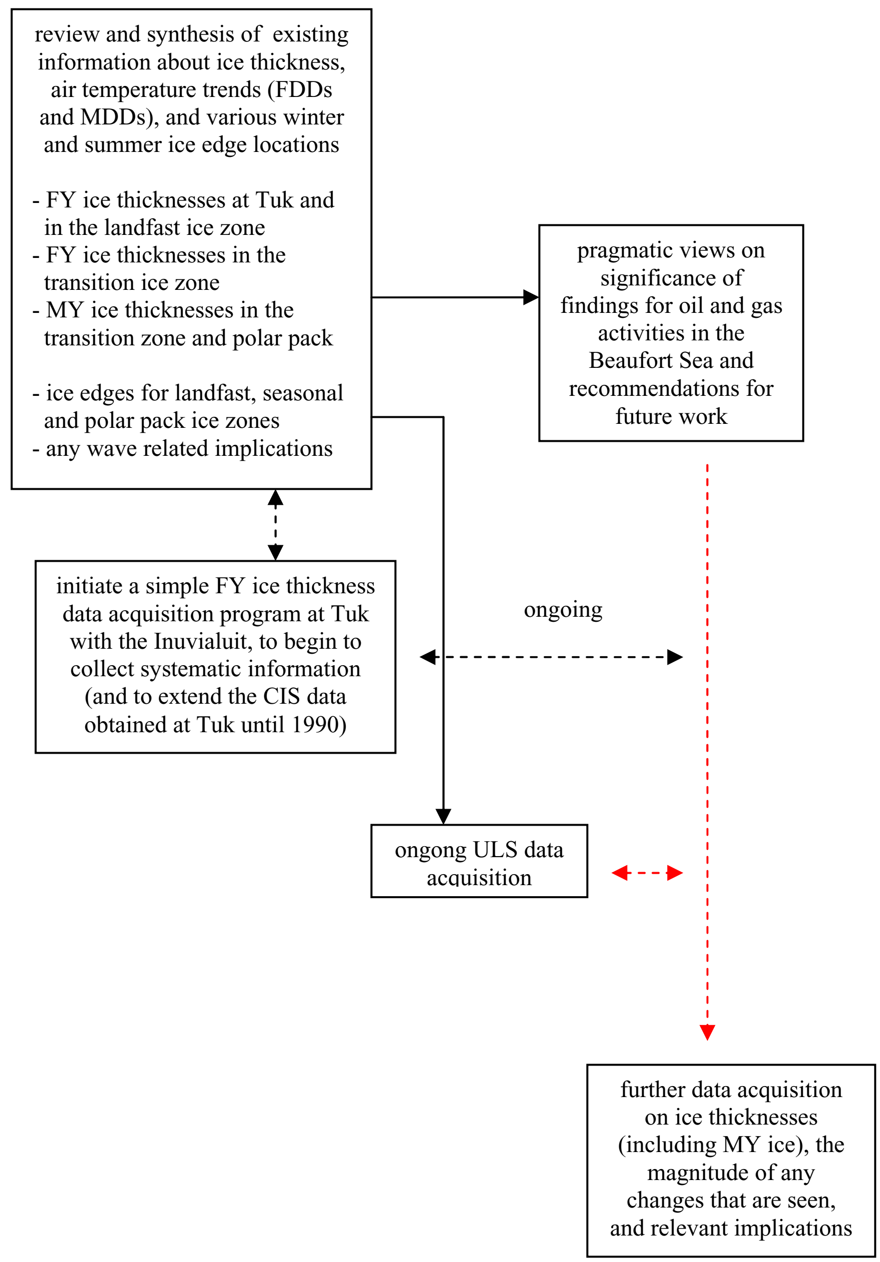

Figure 7.3:

R&D Thrust # 4

Ice Loads on Vessels Station-Keeping in Pack Ice

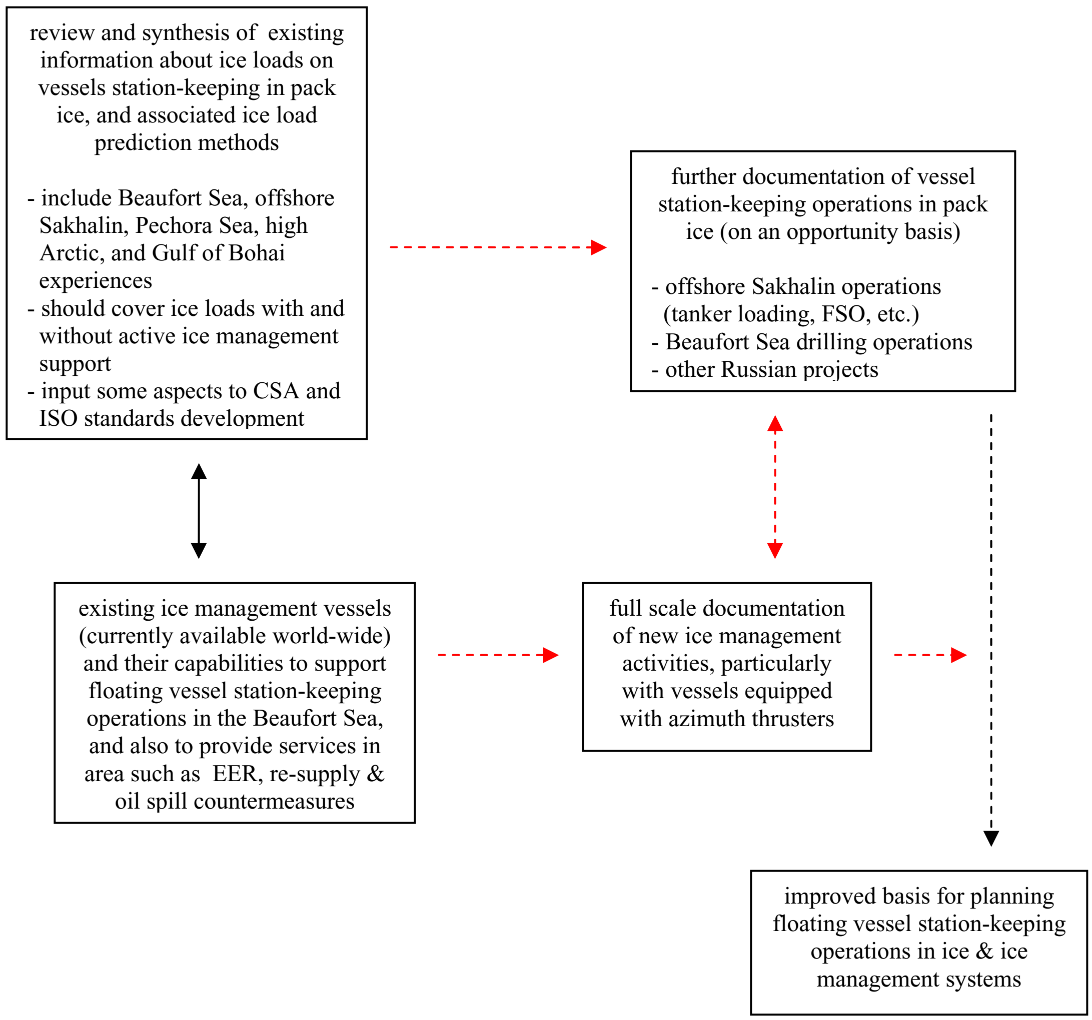

Figure 7.4:

8.0 Closure

This report has presented the results of an ice-related R&D requirements assessment for Beaufort Sea production systems. It has been prompted by a general renewal of interest in the opportunities that may become available for Beaufort oil and gas development projects in the future. As part of this work, key ice-related issues that arose during previous exploration activities in the Beaufort Sea have been identified, along with the ice-related R&D needs that were developed in earlier studies. Discussions with representatives from industry, government and expertise groups have also been held as part of this work, to get their views on current ice-related uncertainties and challenges for potential Beaufort Sea developments.

The key ice-related R&D needs that have been identified in this assessment fall into the following topic areas:

- Design ice loads on fixed structures, including:
  - global loads from extreme multi-year ice feature interactions
  - grounded ice rubble formations & their effect on reducing design ice load levels
- Vessel station-keeping in ice (e.g.: tanker loading) & related ice management aspects
- Ice scour and its influence on the design of seafloor facilities
- The engineering implications of climate change on Beaufort Sea ice conditions
- Improved oil spill countermeasures and clean-up methods in ice
- Improved EER methods for platforms operating in ice-covered waters

Other important messages that have been received as part of this ice-related R&D requirements assessment include:

- a recognition that many of these ice issues are generic, and also of interest for offshore projects in other ice-covered regions of the world
- a recognition that collaborative and cooperative R&D work makes good sense in some ice issue areas, and interest in possible JIP approaches from some companies
- a recognition of the importance of resolving any outstanding technical issues in a timely manner, despite the view that environmental and socio-economic factors may be of more consequence for future Beaufort Sea projects
- a recognition of the ice-related R&D work that has been carried out through PERD and other programs, since the downturn in interest in the Beaufort Sea seen in the late 1980s
- a warning about the need to manage expectations regarding potentially high levels of industry activity in the Beaufort Sea, at least in the short term, because most companies have no firm plans at present, and are just beginning to revisit possible opportunities in the area

On the basis of this assessment work, four specific R&D thrusts have been recommended for further consideration, and a suggested logic framework outlined for each one of them. These R&D thrusts are intended to address high priority ice issues where there is either limited information, or where a front-end synthesis of information would be both timely and beneficial. They include:

- Multi-year design ice loads on fixed structures
- Ice loads on structures surrounded by grounded rubble ice fields
- Ice loads on vessels station-keeping in pack ice
- Engineering and operational implications of climate change on Beaufort ice conditions

The PERD Ice Structure Interaction Advisory Committee (ISIAC) is seen as fostering these ice-related R&D initiatives, with groups such as NRC-CHC and DFO-IOS carrying out much of the work. Other topic areas like ice scour, oil spills in ice, and EER systems for ice-covered waters are also viewed as ones of high importance, but are considered as being well handled at the present time through other programs and initiatives.

9.0 References

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