Full scale experience with Kulluk stationkeeping operations in pack ice (with reference to Grand Banks developments)

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The National Research Council of Canada
(on behalf of PERD Sub-Task 5.3 Oil & Gas)

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by

B. Wright & Associates Ltd.

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Abstract

This report addresses the question of moored vessel stationkeeping operations in pack ice, on the basis of full scale experience with the Kulluk in the Beaufort Sea. As part of this work, a data base which documents full scale ice load levels on moored vessels has been significantly extended, and now includes almost 700 individual ice loading events. In addition, more operationally oriented information about ice management support activities and levels of risk (alerts) has been blended with the load data, for each event. Various scatter plots of expected ice loads in managed pack ice conditions are presented. Data relating to the effect of different levels of ice management support on load and risk levels is also included.

The implications of this information are outlined in relation to various moored vessel system operations in Grand Banks pack ice conditions. It is shown that moored vessel operations in the type of pack ice conditions periodically encountered on the Grand Banks should be less difficult than is currently perceived, provided systems with reasonable in-ice capabilities and adequate levels of ice management support are used.

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1.0 Introduction

1.1 General

The Grand Banks, which lies off the east coast of Newfoundland, is developing into Canada's major conventional oil producing region. The area has estimated recoverable reserves of 1.6 billion barrels of oil and over 3 trillion cubic feet of gas, with potential reserves that are far in excess of these numbers. Oil production from the Hibernia field has been underway for the past several years, centred around the use of a fixed (GBS) platform, installed there in 1996. Daily production on the GBS is now running at about 150,000 BOPD. More than 700 million barrels of oil recovery is expected from Hibernia over the next twenty years. The next major Grand Banks development project, at Terra Nova, is rapidly taking shape. This field has estimated recoverable oil reserves of 405 million barrels and will be produced with a floating development system. The central component of this system is a floating production, storage and offloading vessel (FPSO), which has been built and is now awaiting installation at Terra Nova. First oil production from this field is scheduled to commence in early 2001. Future developments are expected at the Whiterose (180 million barrels) and Hebron (195 million barrels) discoveries, where recent delineation drilling has better defined oil reserve estimates. A number of smaller oil fields have also been discovered in the area but these are currently viewed as uneconomic. Exploration activity continues on the Grand Banks, with some plays moving into deeper water areas towards the north and east, where more severe iceberg and pack ice conditions are found. It is in the interests of Canada and Newfoundland that oil and gas development in the Grand Banks region proceeds, since these developments will create significant wealth, both nationally and provincially.

The current trend for future oil field developments on the Grand Banks is towards the use of floating production systems, similar to the Terra Nova approach. When compared to fixed platform developments like Hibernia, floating systems offer the advantages of lower capital costs and shorter time frames to first oil, particularly as water depths increase. There is little doubt that floating systems will continue to be the preferred option for small to moderately sized oil field developments on the Grand Banks, with the possible exception of reserves that can be easily "tied back" to existing production platforms by subsea pipelines. Some of the technical uncertainties surrounding the design and use of these systems, particularly in relation to the ice conditions that are found on the Grand Banks, remain as priority considerations. From an environmental perspective, the Grand Banks is well recognized as one of the most hostile operating environments in the world, since it experiences high waves, icebergs, and occasional pack ice intrusions. Strong winds, cold waters and poor visibility are additional factors of concern. However, it is the presence of icebergs and pack ice that make the Grand Banks different from most other offshore oil and gas areas, imposing unique constraints on conventional design and operating practices.

Key ice problems that are associated with the design and operation of various Grand Banks development systems were identified in a recent PERD planning report, on a scenario by scenario basis. This report, entitled "Ice Problems Related to Grand Banks Petroleum Fields" (Wright et al, 1997), has been used to guide some of the R&D initiatives undertaken by PERD over the past several years. In this regard, key ice issues include:

- iceberg impact loads on fixed and floating platforms
- iceberg management techniques and their effectiveness
- iceberg scour in relation to subsea pipelines and facilities design
- moored vessel stationkeeping in pack ice

All of these ice issues continue to be of high interest to industry and to the regulators, and accordingly, are being addressed as part of PERD's overall program. The results of R&D in these topic areas, combined with ongoing communication between "the operators and the researchers", should be of considerable benefit for future Grand Banks developments.

In this report, some of the key questions surrounding the use of moored vessels (eg: FPSOs, tanker loading systems) in Grand Banks pack ice are pursued. These include expected ice load levels, appropriate ice management methods, and means of mitigating risk. This work is based on previous operating experiences and ice load data, acquired primarily in conjunction with Kulluk operations in the Beaufort Sea. It is an extension of two recent PERD studies in which the question of moored vessel stationkeeping in Grand Banks pack ice was first addressed (Wright et al, 1998), then a full scale ice load data base developed and "exercised" to assess expected pack ice loads on representative Grand Banks systems (Wright et al, 1999).

NRC, on behalf of PERD, has contracted B. Wright & Associates Ltd. to carry out this study, as a supplement to these two previous reports. The study results are presented in subsequent sections of this report.

1.2 Objectives

The main purpose of this study is to document full scale information that is relevant to the question of moored vessel stationkeeping in moving pack ice, with particular reference to floating development systems on the Grand Banks. To meet this objective, a recent full scale data base regarding ice loads on moored vessels (Wright et al, 1999) has been extended. In addition, more "operationally oriented information" about various ice management activities has been blended with it. In this regard, it is important to note that ice loads are only one part of the overall consideration. The use of ice capable equipment, systematic ice management methods, and well defined in-ice operating procedures are all essential parts of the equation for safe and effective operations with moored vessels in pack ice.

The more specific objectives of this study are:

- to review historical information about the Kulluk's stationkeeping operations in the Beaufort Sea and extract at least additional 100 events (over and above those in the original data base) that provide quantitative information on ice loads, including:

    - the time of each load event, and the pack ice conditions and movements that were associated with each event
    - the ice loads that were experienced during these events
    - the level of ice management support at the time of each load event, and other relevant operational factors such as the "ice alert status" during each event

- to analyze this new full scale load data for trends related to load levels on moored vessels in pack ice, and to compare it to / combine it with the original data base to illustrate salient points

- to highlight some of the key experiences gained with Kulluk operations in pack ice, including the types of ice management methods employed to reduce ice load levels and related risks, and the "results obtained"

- to discuss the implications of this full scale information and experience for floating development systems in Grand Banks pack ice conditions

1.3 Approach

The approach that has been taken in this work is quite straightforward. It has been designed to address the following basic questions.

- what load levels have been experienced, and should be expected, on moored vessels in different pack ice conditions ?

- what types of ice management activities have been used to reduce the load levels on moored vessels in pack ice and to mitigate risk ?

- what are the implications of this experience for floating development systems used in Grand Banks pack ice conditions ?

This report is structured along the lines of these three "areas of concern". For readers who have not yet reviewed the two earlier reports (Wright et al, 1998 & 1999), Section 2 provides some additional background. In Sections 3 and 4, new full scale load event data and related analyses are presented, in combination with information from the original data base. Sections 5 and 6 then highlight the range of ice management systems and methods that were used to support Kulluk stationkeeping operations, along with the results they produced. In Section 7, the implications of this full scale information and experience are discussed in the context of the types of floating development systems that may be used on the Grand Banks.

At this stage, it is important to note that no production operations have yet been carried out from floating systems in moving pack ice, anywhere in the world. This comment applies for moored vessel systems like the Terra Nova FPSO, and for tanker loading operations like those being carried out at Hibernia. The majority of the relevant experience regarding moored vessel operations in pack ice comes from the Beaufort Sea, from Canmar's drillships and more particularly, from the Kulluk . However, these operations involved drilling vessels, which are clearly different from floating production platforms or moored tankers that are loading oil. Nevertheless, the learnings from these Beaufort Sea activities are significant. The information that is given in this report, and in the full scale data that underlies it, represents a unique source of "real world data" for future development activities on the Grand Banks, and for other ice infested regions of the world where moored vessel stationkeeping operations are being considered.

2.0 Background

2.1 General

The information contained in this report is an extension of earlier work, and is based upon two "key ingredients". The first is the Kulluk system itself, and the data and experiences obtained during its operations in the Beaufort Sea. The second is a recent PERD study, entitled an "Evaluation of Full Scale Data for Moored Vessel Stationkeeping in Pack Ice" (Wright et al, 1999), which has been used as the primary "stepping stone" for this work. Because of the central importance of these two ingredients, more background about them is given below, as a precursor to the remainder of the report. This information repeats some of the material contained in earlier studies, but is necessary to include, for completeness.

2.2 The Kulluk

Some History

Ice reinforced drillships and a conical drilling unit, named the "Kulluk", were used for drilling operations in the intermediate to deeper waters of the Beaufort Sea (20 - 80m) from the mid 1970s to the early 1990s. The first drilling operations were undertaken by Canmar's drillships, which were primarily intended for open water use, and normally drilled during the Beaufort's summer and early fall seasons. However, with icebreaker support, they soon developed the capability to stationkeep in a variety of pack ice conditions. This extended their operating season beyond the open water period, although they did not work extensively in heavy ice.

The Kulluk was designed as a second generation drilling system that was purpose built to significantly extend the open water season, by beginning drilling operations in the spring break-up period and continuing until early winter. As a result, the Kulluk operated in a much wider and more difficult range of pack ice conditions than Canmar's drillships. In addition, "in-ice performance information" was systematically obtained during its operations. Because of this, the Kulluk's experience base provides the best source of data for most considerations related to moored vessel stationkeeping operations in various pack ice conditions.

Key Features

The Kulluk was designed with a variety of features to enhance its performance capabilities in ice. Some of the primary technical challenges that were considered and accommodated in the Kulluk's design are highlighted as follows.

- minimizing the icebreaking and clearance forces that the vessel would experience from any direction, by providing it with an "omnidirectional capability" to resist ice action

- developing a hull form that would "minimize" icebreaking forces, enhance ice clearance and reduce the possibility of ice moving down the hull and under the vessel, where it could interfere with the mooring and riser systems, and enter the moonpool area

- providing a strong mooring system that could resist the "high" load levels associated with heavy pack ice conditions during extended season operations, with acceptable mooring line tensions and vessel offsets

- developing a submerged mooring system that would "eliminate" the problem of ice entanglement with mooring lines at (or near) the waterline

- configuring an ice management system that would be capable of "protecting" the Kulluk in the more difficult ice conditions expected in the Beaufort's extended drilling season

Key Kulluk design features are shown in Figure 2.1. In terms of dimensions, the vessel had deck and waterline diameters of 81m and 70m respectively, an operating draft of 11.5m, and a displacement of 28,000 tonnes. It had a downward sloping circular hull form which failed the oncoming ice in flexure at relatively low force levels, and an outward flare near its bottom, to ensure that broken ice pieces cleared around it and did not enter the moonpool or become entangled in the mooring lines. The vessel had a radially symmetric mooring system that, in combination with its circular shape, provided it with a uniform capability to resist ice and storm wave forces from all directions. The mooring system was comprised of twelve 3 ½ inch wire lines and was capable of resisting relatively high forces. These lines were all equipped with RAR's to permit quick disconnects. An important feature of the Kulluk's design was the through hull path of its mooring lines and the underwater fairleads which,

combined with the unit's hull form, reduced the threat of ice fouling the lines.
The Kulluk's hull form provided the unit with good icebreaking and ice clearance capabilities, which reduced ice force levels and in turn, its response motions and the tensions experienced by its mooring lines in ice. Its mooring system was designed to withstand the load from 1.2m of level unbroken ice, when the vessel was operating in a stationkeeping mode, with no ice management support. Given the mooring line lengths, orientations, pretensions and anchor holding capacities assumed during its development, the Kulluk's mooring system was nominally designed to tolerate:

- global loads of 750 tonnes in a drilling mode, within an offset envelope of 5% of water depth (1 -3 m over a 20 - 60m operating range), with maximum individual line tensions of 260 tonnes (50% of their 520 tonne breaking strength)

- global loads of more than 1000 tonnes in a survival mode, with the riser disconnected, when offsets of up to 10% of water depth were acceptable and peak line tensions of 75% of breaking strength were permissible

In practice, the Kulluk was usually deployed with a "less than ideal" mooring spread (eg: various pretensions and sometimes less than 12 lines). This resulted in an overall mooring capacity that was typically in the range of 400 - 500 tonnes in a drilling mode, and 800 - 1000 tonnes in a survival mode. It is interesting to note that these mooring capability ranges are significantly less than those offered by the mooring system on the Terra Nova FPSO, which can resist load levels in excess of 2000 tonnes.

Good ice management was a very important factor in enhancing the Kulluk's stationkeeping performance in ice. Typically, the Kulluk was supported by between two and four CAC 2 icebreakers (Figure 2.2) during its operations in heavy pack ice conditions. Although the vessel occasionally operated in unbroken ice, it normally worked in managed ice conditions, where the oncoming pack ice cover had been prebroken into relatively small fragments by the support icebreakers. In part, this reflects the fact that one or more icebreakers were almost always present in the general vicinity of the Kulluk during its stationkeeping operation in ice. More importantly, it reflects the reality that large expanses of level ice are relatively rare in the Beaufort's pack ice cover. Consequently, ongoing ice management was usually required to fragment the ridges, rough ice areas and thicker old floes that are commonly interspersed throughout the pack, to keep anticipated mooring load levels, line tensions and vessel offsets within acceptable limits.

Operating Experience

After entering the Beaufort Sea in 1983, the Kulluk drilled twelve wells at seven different locations over the 1983 to 1993 period, in water depths ranging from 25 to 50 m. In its role as an extended season drilling system, the Kulluk began operations as early as late May and continued working until late December. Activities were usually suspended because of relief well drilling restrictions, rather than limitations in the in-ice stationkeeping capabilities of the Kulluk itself. During these drilling operations, the vessel was exposed to a wide range of moving pack ice conditions and, with good ice management support, performed extremely well. In this regard, it is important to note that the Kulluk's offset tolerances relative to the wellhead were limited to several metres during its stationkeeping operations. Ice monitoring and well defined alert procedures were also very important contributors to the success of Kulluk operations in difficult ice situations. These procedures helped to ensure that the vessel worked within its performance limits, with safety and efficiency.

The Kulluk's operating capabilities have been well established from its experiences in various pack ice conditions. As noted above, good ice management support was a key element in the success of Kulluk stationkeeping operations, particularly in situations where thick first year ice, pressure ridges, heavy rubble and/or significant concentrations of old ice were present. The pack ice conditions in which Kulluk operated can be subdivided into three characteristic ice seasons, which include:

- spring break-up, with large thick deformed first year ice floes and some old ice
- summer "open water", with heavy first year ice and old ice intrusions
- freeze-up/early winter, with a growing first year pack ice cover and some old ice

Figures 2.3 and 2.4 show representative examples of Kulluk stationkeeping operations in these types of ice situations.

Although the Kulluk often operated in severe pack ice conditions, the amount of ice related downtime that was incurred was low. For example, during its first six operating seasons in the Beaufort (1983 to 1989), involving a total of 585 operating days, the Kulluk experienced 45 down-days and 8 moves off location, and an operating efficiency of more than 90%. These ice downtime events were the result of “red and black alerts” called within the Kulluk's alert system, which was designed to ensure prudent operations in ice, as discussed later.

Ice and performance monitoring programs were used to provide real time support for Kulluk stationkeeping operations in the Beaufort Sea. Because of this, an extensive data base was gathered on the mooring loads and motions experienced by the vessel in different pack ice conditions, and the effectiveness of the ice management methods used. Since much of this Kulluk information is relevant to the more generic question of moored vessel stationkeeping in moving pack ice, it forms the primary basis for this study, and for most of the earlier work that has been done.

2.3 Full Scale Data Base

As noted earlier, a recent PERD study, entitled “Evaluation of Full Scale Data for Moored Vessel Stationkeeping in Pack Ice” (Wright et al, 1999), has been used as the key stepping stone for this work. In terms of scope, this study included:

- a search for and review of full scale data regarding loads on moored vessels in pack ice, from:
  - information obtained during operations of the Kulluk and Canmar drillships in Beaufort Sea ice conditions
  - relevant information obtained from various vessel performance trials, and from other ship operating experiences in ice
- the development of a full scale data base from selected “events” that gave quantitative information about loads on moored vessels in different pack ice conditions
- an evaluation of this full scale data in the form of combined scatter plots, which tied all of the information together in the context of expected load levels on moored vessels in pack ice

- a comparison of the full scale load data with information from a companion PERD project (Comfort et al, 1999), which dealt with loads on moored vessels from model tests

- an application of the full scale data to estimate expected load levels on moored vessels in Grand Banks pack ice conditions, for representative floating development systems

Some of the key results of this recent PERD study are highlighted as follows, since they are an important part of the context for this report.

Ice Load Data

Firstly, a unique full scale data base was developed, containing an unparalleled source of "real world" information about loads on moored vessels in a wide range of pack ice conditions. This original data base has been extended, but also used as a touchstone, in the current study work. By way of summary :

- information that was acquired in conjunction with Kulluk drilling operations comprised the majority of the original data base, and included 384 different ice loading events. This data formed the "backbone" of the work, because of both the quality and quantity of the Kulluk data.

- although Canmar gained a great deal of operating experience with their Beaufort Sea drillships, there was very little documentation around their operations, particularly in terms of the load levels experienced by their drillships in ice. Since there was basically no quantitative information from Canmar's operations that was either available or could be meaningfully used, this data source was necessarily excluded.

- relevant information from vessel performance trials and other in-ice ship operations was not found to be particularly plentiful, with only 26 additional "ship events" included in the original data base. However, these ship entries were a meaningful component of the work, since comparisons with the Kulluk loading information showed that all of the data tied together sensibly, and formed a consistent and credible pattern.

Evaluation of Load Data

The data base was "exercised" to evaluate the load levels and trends that it suggested, as a function of various ice parameters. Of particular importance were scatter plots of the Kulluk load event data for the following ice and ice interaction situations.

- loads in level unbroken ice
- loads in unbroken ridges
- loads from floe impacts
- loads in managed ice with good clearance
- loads in "tight" managed ice with poor clearance
- loads in situations involving "ice pressure"

An evaluation of the Kulluk load data showed very clear and logical trends. As noted above, comparisons between the Kulluk and ship data were also made, which indicated that all of the full scale information tied together well, in a consistent and credible way. Examples of some of the key results generated from the original load data are given in Figures 2.5 to 2.7.

Comparison with Model Tests

The full scale load data was also compared with the results of relevant physical model tests carried out with moored vessels in moving ice conditions. Comparisons were made for unbroken and managed level ice situations, with key model tests involving ones with the Kulluk and several ship shape vessels (a drillship, the Terra Nova FPSO, and tankers moored to a narrow SPM). The level of agreement that was shown between the majority of the model test and full scale load measurements was remarkably good, for equivalent ice interaction situations (see Figure 2.8).

Implications for Grand Banks Developments

The full scale data base was also used to obtain some perspective about expected load levels on moored vessels in Grand Banks pack ice conditions. Representative FPSOs and tanker loading operations were defined for this purpose. Expected load levels on these types of floating systems were shown to be in the range of a few hundred tonnes, depending upon ice thickness, ice movement and ice clearance conditions. Since these load levels are well within the capability of most mooring systems, the work suggested that moored vessel operations in the type of pack ice conditions periodically encountered on the Grand Banks may be less difficult than is currently perceived, providing systems with reasonable in-ice capabilities and adequate levels of ice management support are used.

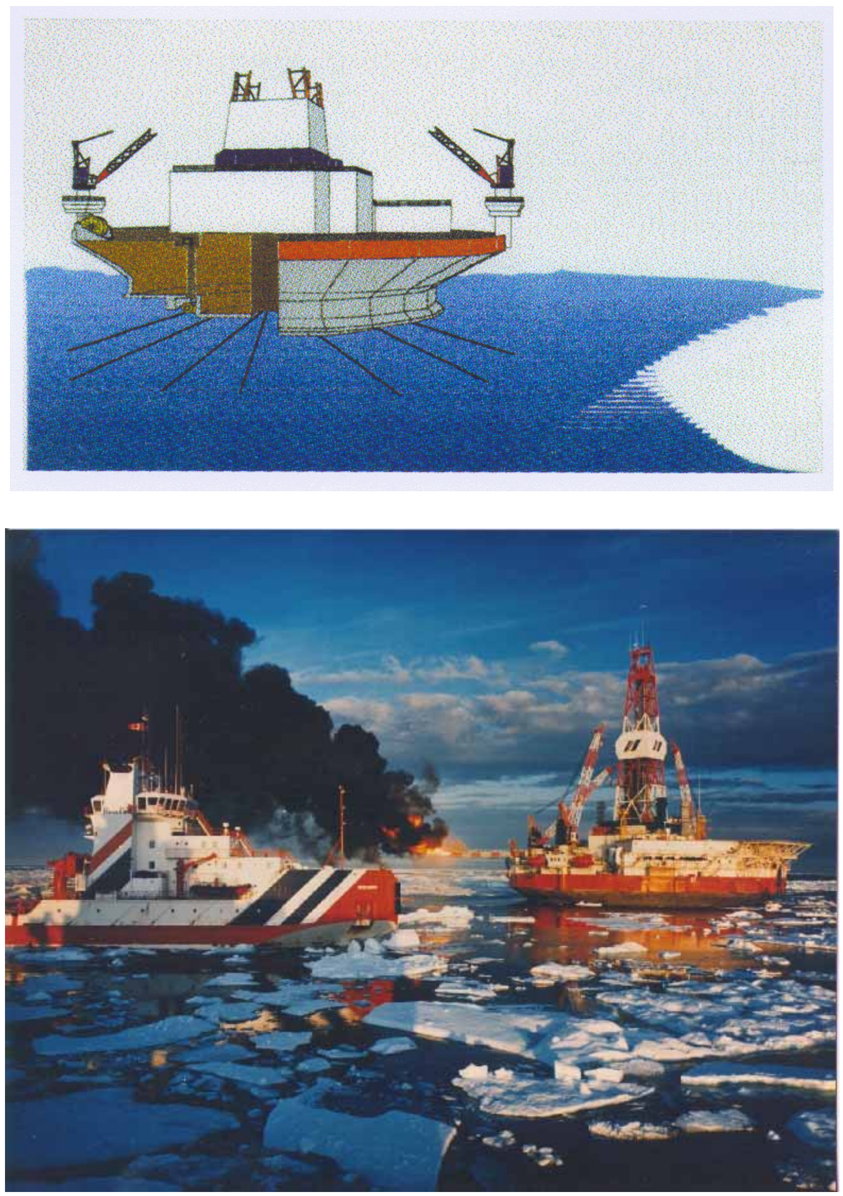


Figure 2.1: The upper part of this figure is a schematic illustration of the Kulluk, which shows some of its key design features. The lower photo shows the Kulluk in the Beaufort Sea, at the Pitsiulak location, where it was testing oil at the time.

Figure 2.2: CAC 2 icebreakers provided very effective ice management support for the Kulluk. The upper photo shows two of Gulf Canada's icebreakers, the Terry Fox (24,000 HP) in the background, and the Ikaluk (14,800 HP) in the foreground. Their sister ships were the Kalvik and Miscaroo, respectively. The lower photo shows two of these icebreakers fragmenting a very thick and heavily deformed rubble field that was threatening the Kulluk at the time.

Figure 2.3: The Kulluk often drilled in very difficult pack ice conditions, with good ice management support. The upper photo shows the Kulluk stationkeeping in thick managed first year ice during a heavy ice intrusion. The lower photo shows ice management updrift of the Kulluk, when it was drilling in moving first and second year pack ice that contained thick ridge and rubble fields, from a few hundred metres to several kilometres in extent. A "picket boat" ice management strategy was usually used in these types of situations. The Kulluk and a support icebreaker can be seen in the upper central part of this photo.

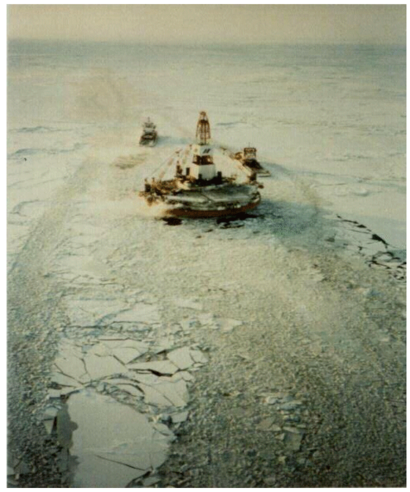


Figure 2.4: The upper photo shows the Kulluk stationkeeping in late freeze-up/early winter pack ice conditions, with two vessels managing the oncoming ice updrift. The ice management technique being used at the time involved tandem linear tracks through the oncoming ice cover. The pack ice was near continuous in terms of its overall concentration, about 1m in thickness, and had frequent areas of ridging and rubble within it. During the late freeze-up/early winter period, poor visibility conditions caused by the long polar night, sometimes combined with fog or snow, were often an impediment to operations, but were successfully dealt with. The lower photo of a “close icebreaker pass” during ice management support activities provides some feel for this type of situation.

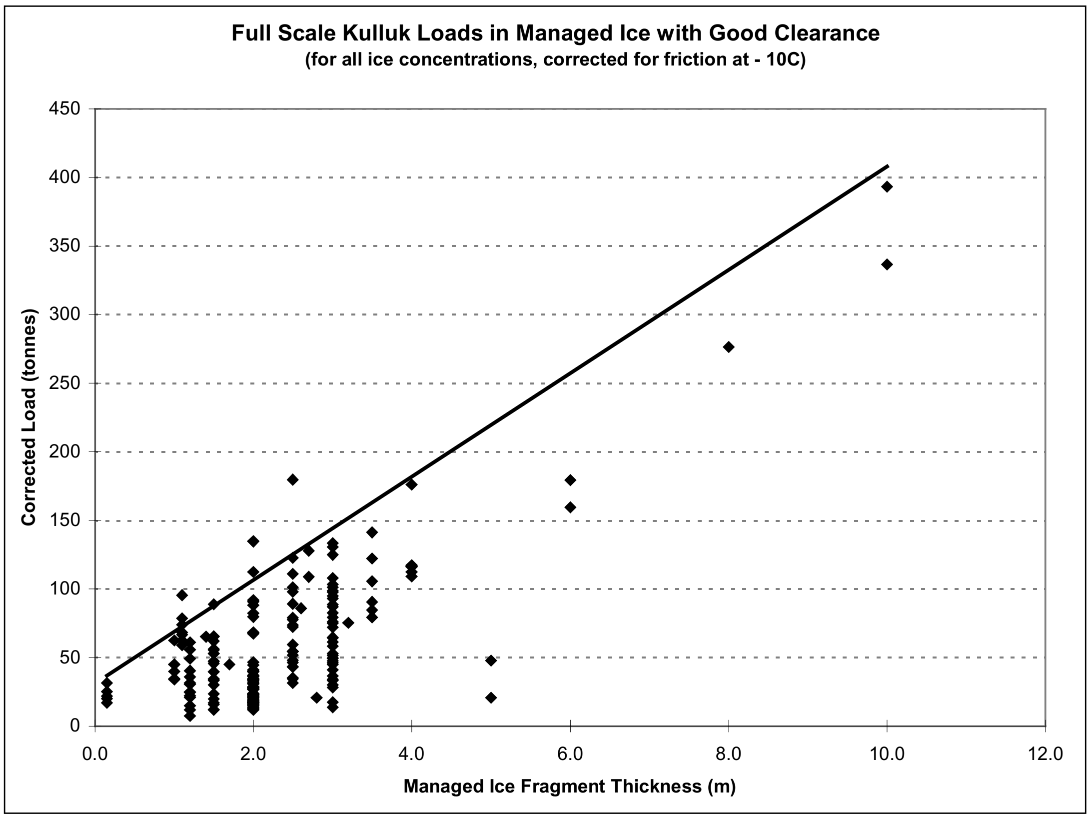


Figure 2.5: A scatter plot of the original Kulluk load event data for situations involving managed ice conditions, with good clearance of managed ice fragments around the vessel. The upper bound line is described by y = 38 x + 31.

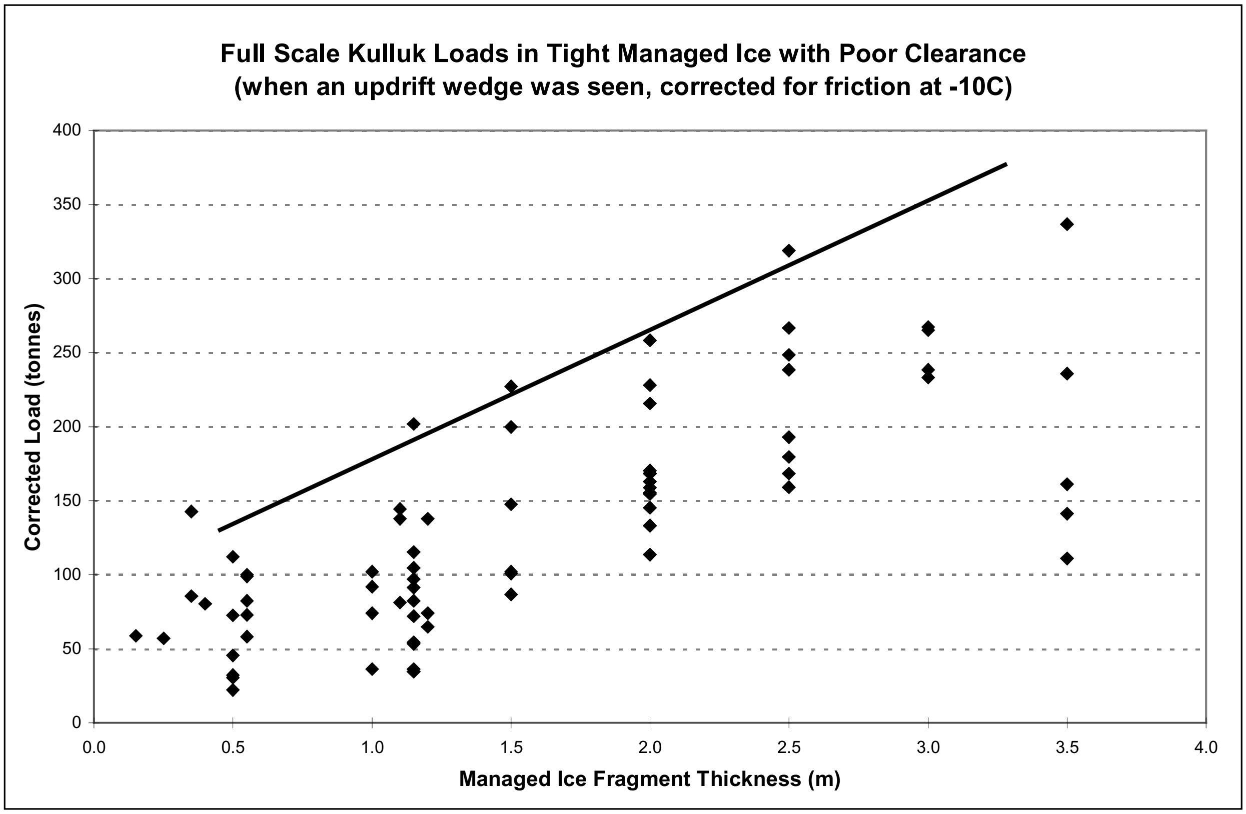


Figure 2.6: A scatter plot of the original Kulluk load event data for situations involving "tight" managed ice conditions, with poor ice clearance around the vessel. The upper bound line is described by y = 87 x + 91.

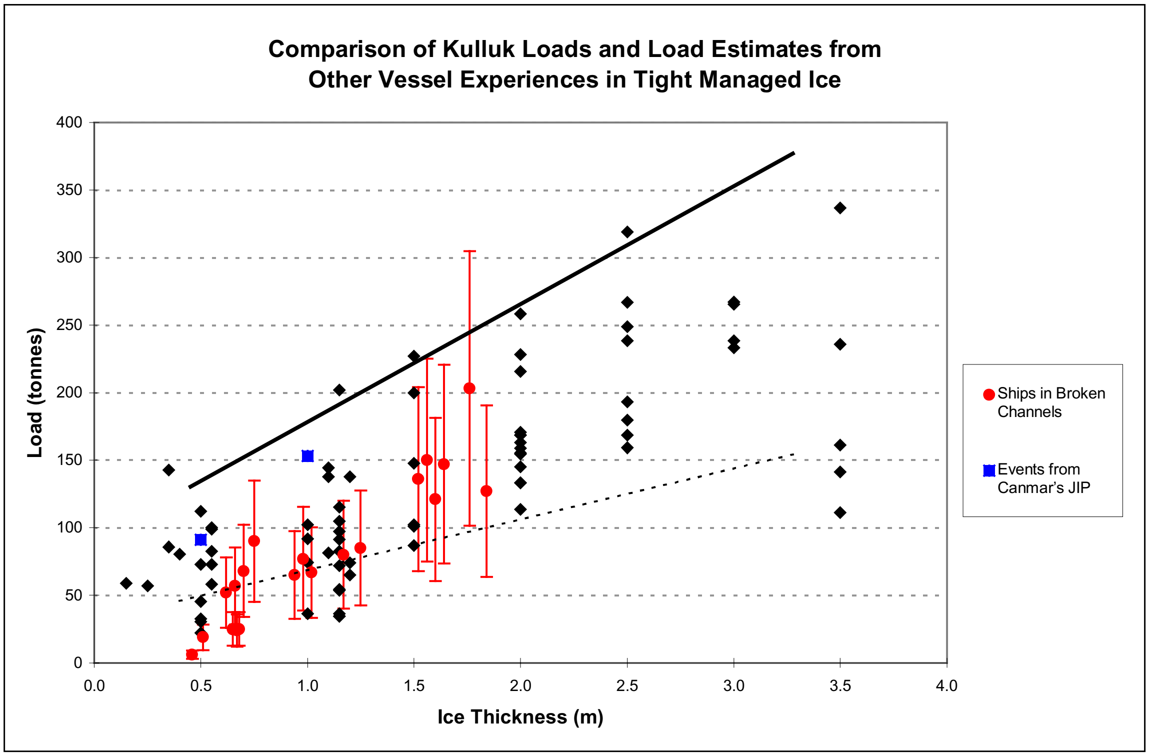


Figure 2.7: A comparison of “other” full scale load event information with the original Kulluk data. The upper and lower bound lines are for managed pack ice conditions, with poor and good ice clearance, respectively. The broken channel ship resistance and Canmar event data points should be expected to fall between these bounding lines because of the type of ice interactions involved, which they do.

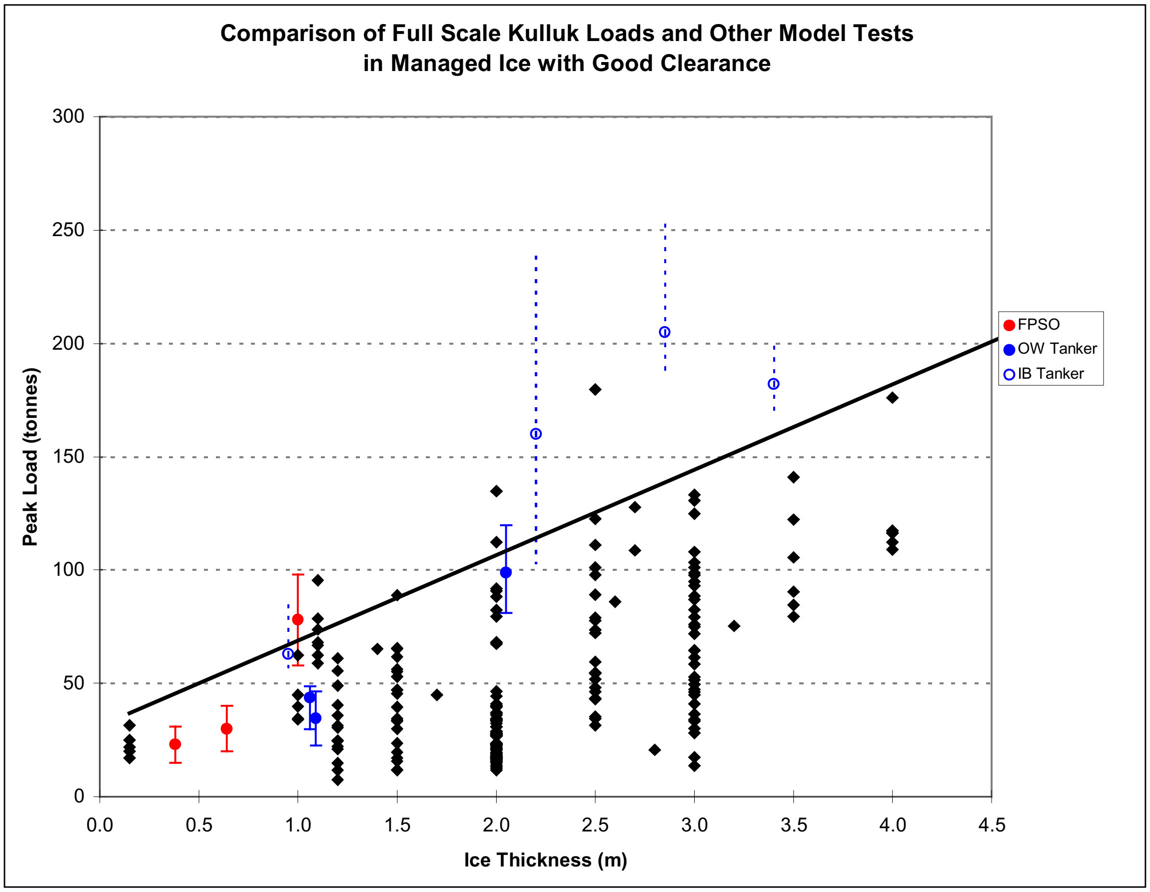


Figure 2.8: A comparison of the original Kulluk load event data with model test results for moored shipshape vessels in managed (prebroken) ice, for similar ice interaction situations.

3.0 New Full Scale Data

3.1 General

In this section of the report, the new Kulluk load event data is introduced and highlighted. As outlined earlier, one of the primary objectives of this study was to locate and extract at least 100 additional events which provide information about ice load levels, over and above those contained in the original data base. This task was time consuming, and involved about half of the overall study effort. In this regard, it is important to note that an underlying objective of the work was to “capture” relevant Kulluk information collected many years ago, before it becomes lost forever with the course of time.

In terms of adding new load information to the original data base, there were two different approaches to choose from. The first involved extracting more events from the chart records used in the original data base development work. These records are detailed, and can be used to associate specific ice interactions with specific load events. However, with this approach, the same basic time periods and ice conditions reflected in the original data base would be treated, and new data added within these “boundaries”. Since these records were used as the primary basis for selecting a representative range of events in the original work, it was felt that further data extraction from them would simply result in “more of the same”. In short, all of the high quality load event information had been analyzed, quite exhaustively and in a representative way, in the original work. The second approach, which was the one adopted in this study, was to find new load event data for time periods not contained in the original data base. Compromises were involved, because other data sources did not necessarily have the same level of “completeness” as the chart record data, at least from a scientific point of view. Truly new data sources about ice load levels were contained in various drilling and barge reports, produced daily, as a routine part of the Kulluk’s operation. These reports lack detail about specific ice interactions but provide good information about the ice conditions in which the Kulluk was operating and the loads experienced, along with the ice management support and “ice alert status” in place at the time. The use of this more operationally oriented data, which contained new days, months and years of ice load event information, was felt to be a more meaningful way of extending the full scale data base. In addition, the information about ice alert levels is relevant and has been incorporated here, as a basis for discussing some of the issues relating to ice management and mitigation of risk.

3.2 Data Sources

The various sources of Kulluk data were outlined in considerable detail in the "original full scale data" report (Wright et al, 1999), together with illustrative examples, and will not be repeated here. Sufficed to say that these data sources contain information about:

- the Kulluk's "as deployed" mooring at each drilling location, including:
  - the number of mooring lines deployed
  - the length and orientation of each mooring line
  - the anchor(s) used on each mooring lines
  - the pretension and operating tension in each mooring line
- the pack ice conditions around the Kulluk during stationkeeping operations, documented by onboard environmental observers on an hourly basis, including:
  - ice concentrations
  - ice thicknesses
  - ridge concentrations and heights
  - floe sizes
  - ice drift speeds and directions
- the ice management vessels being used to support Kulluk operations and sometimes, the type of techniques employed by the icebreakers to manage the ice
- global loads on the Kulluk's mooring system, tensions in its individual mooring lines, offsets from the wellhead, and the vessel's rotational and heave motions, recorded by a real time performance monitoring system (at 1 Hz)
  - an example of the type of global load time series data that was obtained with the Kulluk's performance monitoring system is given in Figure 3.1
  - this type of information, or specific loading events extracted from it, is the basic source of all of the load data contained in the original Kulluk data base, as well as the new load event data that has been added in this work

As noted earlier, the new Kulluk load event information contained in this study comes from "less detailed" data sources than the original chart records, such as daily barge and drilling reports. Examples of these types of data sources are shown in Figures 3.2 and 3.3, with key entries highlighted in yellow. Although provided in summary form, it is important to recognize that the basic data contained in these reports was originally extracted from the chart records and ice observation sheets onboard, albeit in an operational setting. As such, it is of the same quality as the "more detailed data records" which are no longer available for the new time periods considered in this work.

In addition to providing information about ice loads, ice conditions, and ice management levels, these summary reports also specify the ice alert status that was in place at the time. This alert information is useful and has been included as an entry with the new Kulluk load event data. It has also been extracted for all of the original ice loading events and added as a new data base entry for each one of them.

As was the case in the original full scale data evaluation work, other sources of information were reviewed in combination with the data contained in the daily barge and drilling reports. These other data sources, which are highlighted below, were used to supplement some of the new load event information, where possible and when necessary.

1983 Kulluk Performance Summary	- an internal Gulf Canada report
1984 Kulluk Performance Summary	- an internal Gulf Canada report
1985 Kulluk Performance Summary	- an internal Gulf Canada report
1988/89 Kulluk Operations & Performance Report	- a report prepared by PFL for Gulf Canada
Floating Drilling System Study	- a report prepared by Beaudril & Canatec for an international client

Environmental Observation Reports	- end of season summary reports prepared for each Kulluk site

3.3 Data Base Additions

The type of information that was extracted for each new Kulluk load event followed the same data entry format as in the original data base. This format includes entries which identify "all of the important factors", within the logic framework shown below. The intent of this logic is to highlight key areas of concern, from the perspective of "operations on the bridge".

knowledge of the capabilities & limits of the Kulluk's mooring system

↓

knowledge of the pack ice conditions updrift of the Kulluk

↓

the effectiveness of the ice management provided   *ice alert status*

↓

managed ice conditions near the Kulluk

↓

load levels on the Kulluk

The entries in the Kulluk data base are configured along these lines. General information is given first, including:

- the location of the Kulluk's operation
- the characteristics of the vessel and its mooring system
- the date and time of each load event

The remaining entries provide information about other relevant factors, such as:

- the pack ice conditions updrift of the Kulluk
- the ice management support that was in-place

- the loads that were experienced

Two supplementary entries have also been added for the new Kulluk load event information, and retroactively, for all of the loading events contained in the original Kulluk data base. These are:

- a "pragmatic coding" for the type of pack ice regime in which Kulluk operations were being carried out during each load event
- the ice alert status that was in place during each load event

More specific examples of these data base entries are given below, to provide the reader with some feel for the type of information underlying the various assessments given later in this report. The Kulluk data base, itself, is contained in a large Excel spreadsheet which resides at NRC. It should be noted that this data base remains proprietary to NRC, as its custodian, and to Gulf Canada, as owner of the Kulluk data.

General Information

An example of the first portion of the Kulluk data base is given as follows.

Vessel Name	Vessel Characteristics	Mooring Configuration	Location	Date of Event	Time of Event
Kulluk	see Kulluk description in vessel characteristics sheet	see Kulluk Kuvlum # 2 / 93 mooring description in mooring configuration sheet	Kuvlum # 2	1-Nov-93	0600
Kulluk	see Kulluk description in vessel characteristics sheet	see Kulluk Immiugak N-05 / 88 mooring description in mooring configuration sheet	Immiugak N-05	3-June-89	0600
Kulluk	see Kulluk description in vessel characteristics sheet	see Kulluk Aagnerk E-56 / 86 mooring description in mooring configuration sheet	Aagnerk E-56	26-June-86	-
Kulluk	see Kulluk description in vessel characteristics sheet	see Kulluk Nerlerk J-67 / 85 mooring description in mooring configuration sheet	Nerlerk J-67	20-Oct-85	-

Pack Ice Conditions

The second grouping of entries deals with the pack ice conditions and movements that were seen near the Kulluk during each loading event. Most of these ice conditions entries are self explanatory. An example of this portion of the data base is given as follows.

Total Ice Concentration *(10ths)*	***Concentration by Type*** *(10ths)*	***Ice Thickness by Type*** *(m)*	***Typical Floe Size*** *(m)*	***Larger Floe Sizes*** *(m)*
9	5 - G 4 - GW	0.1 0.15 - 0.3	100 - 500	500 - 2000
2	2 - TFY	1.5	500 - 2000	2000 - 10000
8	8 - TFY	1.5	500 - 2000	2000 - 10000
9+	9 - TFY trace - SY	0.3 2 - 3	500 - 2000	2000 - 10000

Ridging Concentration *(10ths)*	***Typical Ridge Sail Height*** *(m)*	***Typical Keel Depth*** *(m)*	***Larger Ridge Sail Heights*** *(m)*	***Larger Keel Depths*** *(m)*	***Related Comments***
insignificant ridging	-	-	-	-	thin growing first year pack ice cover, quite level with some rafted areas
1 - 2	0.5	3 - 4	1.0	4 - 6	low concentrations of thick first year pack
2 - 3	1 - 2	5 - 10	2 - 3	10 - 15	thick first year pack ice with some areas of moderate ridging and rubble
1 - 2	0.5	3 - 4	1.0	4 - 6	thin growing first year pack ice cover with some small old ice floes

Ice Drift Speed *(m/sec)*	***Ice Drift Direction*** *(degrees true)*	***"State" of the Ice Cover***	***Flexural Ice Strength*** *(kPa)*
0.38	135	very close pack, with insignificant roughness	247
0.2	90	open pack, with a few ridges and low lrelief rubble areas	180
0.3	20	close pack, with areas of significant ridging and roughness	180
0.25	100	very close thin pack under pressure	483

Of all these ice data entries, the only parameter that was not observed nor measured during Kulluk operations is the flexural ice strength. Accordingly, ice strengths had to be estimated from other parameters, in particular, from air temperature data. The approach that was used to approximate flexural ice strength values is highlighted as follows.

- firstly, the mean ice temperature was estimated from the ambient air temperature, using the assumption of a linear temperature profile through the ice

- when the air temperature was above freezing and the ice was not reported as either "weak or rotten", it was assumed to be isothermal at - 2°C

- when the ice was reported as being weak, it was simply assigned a flexural strength of 180 kPa and when it was termed rotten, it was assigned a strength value of 150 kPa

- for each one of the other event cases where the ice was at - 2°C or lower, the following procedure was used:

  - the bulk ice salinity was determined on the basis of the ice thickness (Kovacs, 1997) as

$$S = 4.6 + 91.6\ h$$

  - the brine volume was then determined from the calculated salinity and estimated ice temperature as (Kovacs, 1997)

$$v = S\,(0.532 - 49.2 / T)$$

- the flexural ice strength was then determined from the estimated brine volume (Timco & O'Brien, 1994) as

$$\sigma_f = 1.76\, e^{-5.88 \sqrt{v}}$$

The flexural strength values that have been estimated in this manner cannot be viewed with a great deal of certainty, but should not be unreasonable.

Since the new Kulluk load events are all associated with managed ice conditions, the flexural ice strength estimates have not been used explicitly in this work, for any "load normalization" purposes. In this regard, flexural strengths are simply provided as a reference value for each load event in the Kulluk data base.

Other Factors

The third grouping of entries in the data base deals with "other factors" that were observed at the time of each loading event. They include:

- mean daily air temperature (based on measurements made onboard)
- rough estimate of snow cover (entered as light, moderate or heavy: < 10 cm, 10-30 cm, and > 30 cm, respectively)

These data entries are straightforward and are not illustrated here.

Ice Management Support

The fourth grouping of data entries summarizes the type of ice management system that was in place during each Kulluk event. This information gives some feel for the level of icebreaker support being provided when different load levels and alerts were experienced. An example of this portion of the data base is given as follows.

Number of Vessels	*Support Vessels*	*Ice Management Technique*
1	- Miscaroo	not available
2	- Terry Fox - Miscaroo	occasional breaking and floe pushing
1	- Kalvik	not available
3	- ikaluk - Kalvik - Terry Fox	not available

Entries about the number and "specifics" of the support vessels are straightforward, but the ice management techniques employed are not. For the most part, any specific information about the ice management techniques being used at the time of each new Kulluk load event is not available (as it was for many of the original data base entries), and is not included. However, the techniques that were used to contend with the oncoming ice cover in various situations, and reduce ice loads, are discussed in some detail later in this report.

Managed Ice Conditions

From the information that is still available, details about the managed ice conditions in close proximity to the Kulluk cannot be resolved, for most of the new ice loading events. In the original data base, a fifth grouping of entries highlighted the type of managed ice conditions seen at the Kulluk during each event, including:

- local ice concentration
- mean ice thickness
- thicker ice fragments
- typical managed ice piece size
- larger managed ice piece size
- related comments

For most of the new Kulluk load events, these entries have simply been left as blank fields.

However, in pragmatic terms, it is known that typical managed ice piece sizes for the new load events should be in the range of 10m - 50m, since this was the “defined target” for the ice management support system.

Load Events, Alert Levels & Ice Regimes

In the original data base, the Kulluk load events could be quite well described from the chart record time series. As a result, a sixth grouping of data entries was included, which provided the following specifics about many of the loading events.

- type of ice interaction
- best guess ice thickness
- best guess ice fragment size
- peak load
- ratio of peak to mean load
- rise time to peak load
- duration of load event
- comments

Again, this level of information is no longer available for the new Kulluk load events that are presented in this report, because the orginal chart records have not been kept. Although the new load event data is somewhat “less complete”, it still provides hard full scale information about load levels and as such, is of central importance here.

With reference to this sixth data base grouping, the entries that have been included for the new Kulluk load events are:

- the load for each new event
- the best guess ice thickness for each event
- comments

The remaining entries contained in the original data base have necessarily been left as blanks. However, two supplementary pieces of information have been added to this sixth part of the data base, as noted earlier. These are:

- the alert status at the time of each load event (which is an indicator of risk)
- a code for the type of pack ice regime in which operations were being carried out during each load event (which combines information about ice concentrations, thicknesses, ridging and so forth, in a pragmatic yet practical way)

An example of these entries is given below, for the new Kulluk load events. As mentioned earlier, alert status and "pack ice regime" information has also been extracted and included for all the loading events contained in the original data base.

Ice Load on Kulluk *(tonnes)*	***Best Guess Ice Thickness*** *(m)*	***Alert Status Colour Code***	***Pack Ice Regime***	***Comments***
60	0.3	blue	4	high concentrations of thin managed ice
30	1.5	green	2	open pack with managed first year floe fragments
115	1.5	green	8	high concentrations of thick managed ice
124	0.3	yellow	11	thin first year pack under moderate pressure

The Kulluk's ice alert system, and the colour codes which are part of it, are described in Section 5. At this stage, it suffices to say that the green, blue and yellow alerts shown in the foregoing example simply represent increasing degrees of risk. However, further explanation of the coding system that has been used to describe different pack ice regimes is required.

Firstly, the Kulluk information that has been extracted contains fairly good descriptions of the pack ice conditions around the vessel during each new loading event. These conditions form the "basic setting" in which Kulluk stationkeeping operations were conducted at the time of each event, with ice management support. Both the new and the original load event data sets span a wide range of pack ice conditions. In terms of characterizing specific ice situations, key variables include ice concentrations, ice thicknesses, the degree and severity of ridges and rubble, and the presence of old ice floes. Endless combinations of these variables are possible, on an event by event basis.

For the purposes of this work, different pack ice regimes have been defined and assigned a "code number", with the intent of capturing "operationally similar" pack ice settings in a practical and straightforward manner. These group different pack ice situations, with varying ice conditions specifics, into a manageable number of categories, as shown in Table 3.1. The nomenclature that is used in this table follows WMO standards. In this regard, the following definitions are cited, as a reminder.

Ice Type	Thickness
thick first year ice	1.2m - 2.0m
medium first year ice	0.7m - 1.2m
thin first year ice	0.3m - 0.7m
new ice types	0 - 0.3m
old ice (includes second & multi-year)	2.0 - 5.0m (typically)

Floe Size	Dimension
vast floes	2 km - 10 km
big floes	500m - 2000m
medium floes	100m - 500m
small floes	20m - 100m

Pack Ice Regime	***Concentration***	***Thickness***	***Floe Size***	***Other Comments***
2	1 - 3/10ths	- medium & thick first year ice	- typically medium - some small, big & vast	- moderate amount of ridging - some rough ice areas (rubble fields) - moderate to large ridge & rubble heights
3	1 - 3/10ths	- primarily thick first year ice - some old ice present	- typically large - some moderate & vast	- significant amount of ridging & rubble - moderate to large ridge & rubble heights - variable concentrations of old ice
4	8 - 9+/10ths (typically)	- new & thin first year ice	- typically large - some moderate & vast	- low to moderate amounts of ridging - typically low relief ridges & rubble features
5	4 - 6/10ths	- medium & thick first year ice	- typically medium - some small, big & vast	- moderate amount of ridging - some rough ice areas (rubble fields) - moderate to large ridge & rubble heights
6	4 - 6/10ths	- primarily thick first year ice - some old ice present	- typically large - some moderate & vast	- significant amount of ridging & rubble - moderate to large ridge & rubble heights - variable concentrations of old ice
7	7 - 8/10th	- medium & thick first year ice	- typically medium - some small, big & vast	- moderate amount of ridging - some rough ice areas (rubble fields) - moderate to large ridge & rubble heights
8	7 - 8/10ths	- primarily thick first year ice - some old ice present	- typically large - some moderate & vast	- significant amount of ridging & rubble - moderate to large ridge & rubble heights - variable concentrations of old ice
9	9 - 9+/10ths	- medium & thick first year ice	- typically medium - some small, big & vast	- moderate amount of ridging - some rough ice areas (rubble fields) - moderate to large ridge & rubble heights
10	9 - 9+/10ths	- primarily thick first year ice - some old ice present	- typically large - some moderate & vast	- significant amount of ridging & rubble - moderate to large ridge & rubble heights - variable concentrations of old ice
11	9 - 9+/10ths	- full range of thin ice & first year ice types	- usually medium to big	- in-ice pressure (variable degrees of severity)

Table 3.1: Codes for and descriptions of the characteristic pack ice regimes. With the exception of pack ice regimes # 4 and # 11, the code numbers used are very similar to the pack ice concentrations.

Summary

By way of summary, 295 new ice load events have been extracted from the Kulluk data, and included as additional entries in the full scale data base. These Kulluk loading events span:

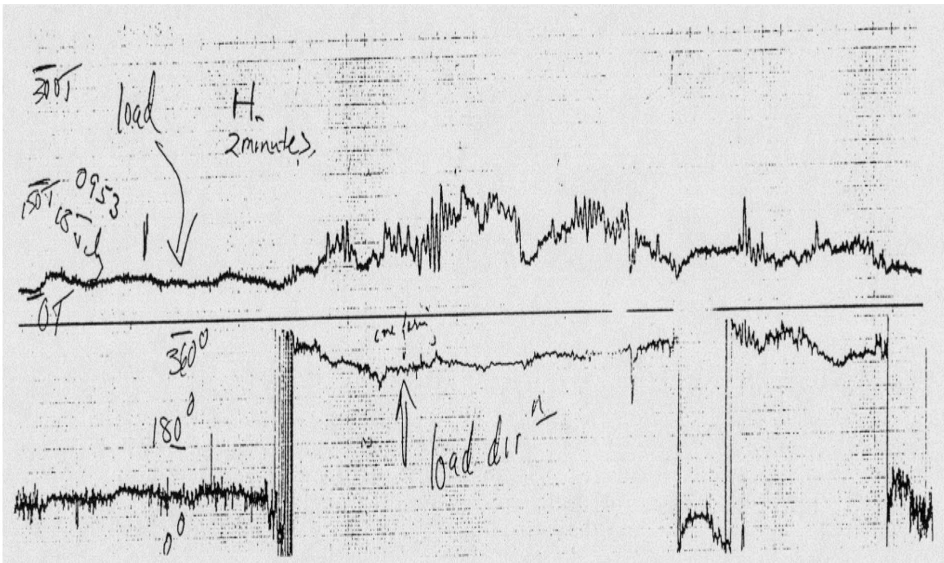
- another two years of Kulluk operations that were not included in the original data base

- more than 150 “new days” of load event data within these two years, and within the five years of Kulluk operations considered in the original work

These new Kulluk events provide more information about full scale ice load levels, again in a wide range of pack ice conditions, and are a significant addition to the 384 events contained in the original data base. Although specific details about the managed ice conditions and ice interactions at the Kulluk are not contained in this new load event data, the following “key and practical” factors are well described:

- the pack ice regime in which the Kulluk was operating
- the ice management support provided
- the loads that were experienced
- the alert status in place at the time of each loading event

The following sections provide an assessment of this new Kulluk event data, plus some of the original data, from the perspective of load levels, ice management and risk.



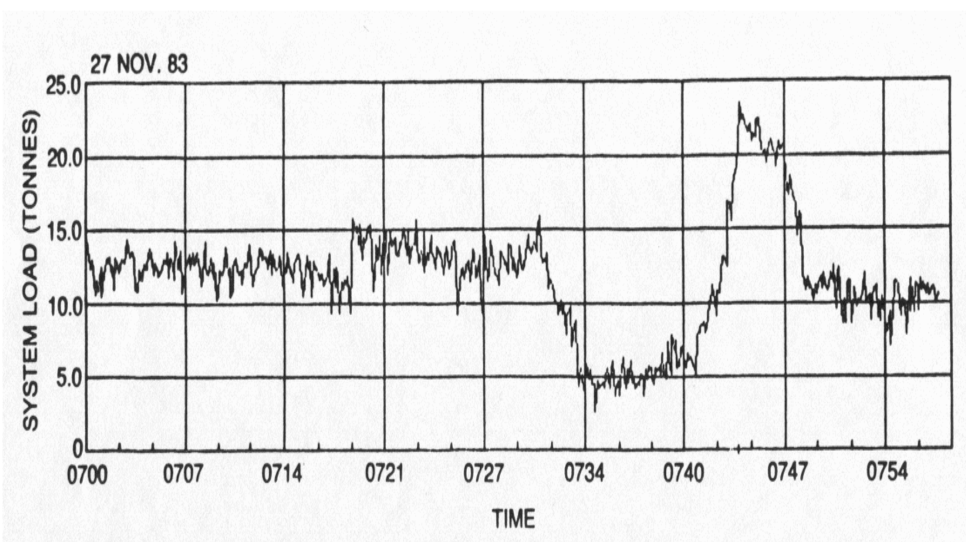


Figure 3.1: Examples of the type of global load time series data provided by the Kulluk's performance monitoring system. The upper part of this figure shows a load trace as obtained in real time onboard, while the lower example is a trace that was post-processed "onshore". These chart records are the basic source of both the new and original Kulluk load event data.

KULLUK Barge Report Belcher

Date: 05-Aug-89 Period: 0000-2359 MDT Lat/Long: 70 16.5 N / 141 30.8 W

ALERT @0400/06 Blue REASON: Fog & Ice HT:15 ST: 8 KT:-1 OT: 7

ENVIRONMENT as of 0400 06/08/89	MAX PAST 24 HRS	ACTUAL 0400	MAX NXT 24 HRS
Ice Conc (tenth):	8/10	8/10	9/10
Ice Thickness (m):	2.0	2.0	2.0
Ice Drift (knots):	0.4	0.4	0.4
Drift Dir. To (degT)	100	100	100
Ice Press.Potential:	No	No	No
Wind Speed (knots):	26	02	18
Wind Direction(degT)	290	140	220
Temp Min (degC):	6	8	10
Visib Min (n.miles):	0.75	0.75	0.5
Global Load (tonne):	101	71	150
Riser Angle (deg):	.56	.19	0.5
Offset (m):	.69	.23	0.75
Roll/Pitch (deg):	.73/.11	.71/.06	0.5
Wave Ht/Per (m/s):	n/a	n/a	n/a
Heave (m):	0	0	0

	miles	degT
Hazard/Ice:	4.0	280
Mvmt past24	5.19	087
Mvmt next24	7.5	090

Remarks/Outlook

Hazardous ice updrift is expected to be managed after moderate heavy ice breaking. Ice beyond 5 miles is easily managable.

(No gyro failures today, T6 senson dead again).

STABILITY DATA

Dspl:28403t	KM:45.8	KB:6.8	KG:14.0	GM:31.8	Dk/Ld:4369	Drft:11.4m	W/D: 52m

ANCHOR SYSTEMS

#	Wire Lgth	Wire Out	Pen	RAR #	Code	Pen	#1 Anc	MMS	F/A	Pen	Brng	#2 Anc	MMS	F/A	Pen	By
1	1130	895	20	171	IJOP	70	20SS	37	32		195					
2	950	859	20	172	IJLP	70	12S	12	32		225					
3	1130	942	20	160	IKNO	70	15M	29	-	70	256	15B	16	30	70	
4	1143	961	20	146	IKLN	70	15B	22	30	70	289	12B	21	30		
5	1000	905	20	143	IJNO	70	15S	9	32		315					
6	1130	1030	20	156	MNOP	70	15HS	40	32		348					
7	1130	928	20	169	IJMP	70	20SS	36	32		015					8
8	1130	909	20	174	IKMN	70	12S	10	32		045					3
9	985	891	20	153	IKLO	70	12HB	20	30	70	075	15L	32	-	70	2
10	1130	907	20	151	IJKM	70	15B	17	30	70	103	12B	14	30	70	7
11	1130	927	20	162	IJMN	70	15B	23	30	70	134	15B	19	30	70	
12	1130	858	20	154	IKNP	70	12S	13	32		165					

2nd piggybacks: #3 - 6 1/2 t trident MMS 35, #10 - 15t LWT MMS 25
#11 - 15t LWT MMS 26 #9 - 15t LWT MMS 24

Anchor Number:	1	2	3	4	5	6	7	8	9	10	11	12
Current Tension:	145	135	145	138	138	140	145	165	120	180	152	170
Peak Tension (24 hr):	150	150	169	195	150	140	170	185	195	200	198	197
Pre-tension:	205	195	190	185	195	205	210	200	195	200	190	200

Figure 3.2: A representative example of the type of information contained in Kulluk barge reports These reports were produced on a daily basis onboard the vessel, as part the operations reporting scheme that was used by Gulf. This example shows the "ice, load and alert" (upper) and "mooring system" (lower) sections of the Kulluk barge report.

SUPPORT VESSELS

Terry Fox	Fuel m3	Bulk Tank Capacity = 3 tanks @ 35 m3 = 105 m3				
M/Capacity	1918.56	Barite	Arcticset	OWG		Location
Onboard	1511.7	195.0				Belcher
Rcvd/Dchrg						Ice management
Used	26.7					
Deck Cargo	1x70m pennant					
Kalvik	Fuel m3	Bulk Tank Capacity = 3 tanks @ 35 m3 = 105 m3				
M/Capacity	1918.56	Barite	Arcticset	OWG		Location
Onboard	1227.0		116.0			Belcher
Rcvd/Dchrg						Ice Management
Used	54.5					
Deck Cargo	Pollution equipment					
Miscaroo	Fuel m3	Bulk Tank Capacity = 4 tanks @ 35 m3 = 140 m3				
M/Capacity	1596.00	Barite	Arcticset	OWG		Location
Onboard	896.5	232				Belcher
Rcvd/Dchrg						Ice management
Used	35.6					Piggyback #9
Deck Cargo	1x15t Bruce, 4x15t Moorfast, 4x20m pennants, 2x70m pennants, 3x50m pennants, 1x40m pennant,					
Ikaluk	Fuel m3	Bulk Tank Capacity = 4 tanks @ 35 m3 = 140 m3				
M/Capacity	1596.00	Barite	Arcticset	OWG		Location
Onboard						
Rcvd/Dchrg						Herschel Basin
Used						
Deck Cargo						

Figure 3.2: (continued) The section of the Kulluk barge report which summarizes the type of ice management support provided over the reporting period.

KULLUK DAILY REPORT (METRIC) PAGE 1 OF 2

FOR THE PERIOD 0000 - 2400: 93/08/01

REPORT	LOCATION: N70 18 W146 32	OPERATOR : ARCO ALASKA	DOWNTIME LAST 24 HRS: 0
DATE: 8/1/1993	WELL: KUVLUM-2	OPER. REP : B. CAMPBELL	CUM. DOWNTIME: 0
	START-UP DATE: JUNE 1 93	O.I.M : D. HOPE	DAYS ON LOC: 14

FROM	TO	OPERATIONS SUMMARY
00:00	01:30	PICK UP SLIP JOINT, PICK UP DIVERTER & LOWER STACK.
01:30	02:30	HOOK UP CHOKE AND KILL LINES.
02:30	03:30	HOOK UP RISER TENSIONERS AND SURFACE LINES.
03:30	05:00	JUMP DIVERS, POSITION RIG AND LAND BOPS - OVERPULL 100,000. DIVERS IN WATER
		03:42 - SURFACE @ 04:46.
05:00	06:00	LAND DIVERTER - HOOK UP PODS.
06:00	07:30	RUN TEST PLUG WITH 4 STDS HWD TAIL PIPE.
07:30	11:00	PRESSURE TEST BOP'S, LOW 250, HIGH 5000 psi - 5 MINUTES EACH. FUNCTION
		YELLOW POD. PRESSURE TEST CASING AND SHEAR RAMS TO 2200 PSI.
11:00	11:30	PULL OUT OF HOLE WITH TEST PLUG.
11:30	13:00	RUN AND SET NOMINAL SEAT PROTECTOR.
13:00	16:00	MAKE UP 17-1/2 DRILL OUT ASSEMBLY AND RIH. TAG CEMENT AT 993' RT.
16:00	16:30	DRILL CEMENT F/993' - 1006' RT.
16:30	19:30	CIRCULATE BOTTOMS UP - DISPLACE HOLE TO 9.8 ppg MUD - SHUT IN WELL
		PRESSURE CASING TO ESTABLISH BASE LINE PRIOR TO DRILL OUT.

ALERT STATUS (hours)

LEVEL	ENVIR	WELL	VESSEL
GREEN	16	24	24
BLUE	8		
YELLO			
RED			
BLACK			
0600	BLUE	YELLO	GREEN

VESSEL MOTIONS/ATTITUDE

	MAX	0600
HEAVE (m)	.2	0
PITCH (sing amp)	.3	0
R.A.(deg)		
OFFPSET(m)		
GLOBAL(mt)	68.0	68.0

STABILITY DATA

Figure 3.3: A representative example of the information contained in Kulluk drilling (or operations) reports. This is one section from a daily Canmar operations report, produced after they had purchased the Kulluk from Gulf, and were operating the vessel off Alaska in 1993. This example shows the "load and alert" section of the report.

ENVIRONMENT INFORMATION	PAST 24 HRS	0600	NEXT 24 HRS	ENVIRONMENT INFORMATION	PAST 24 HRS	0600	NEXT 24 HRS	ENVIRONMENT INFORMATION	PAST 24 HRS	0600
ICE CON.(10ths)	4	5	5	TEMP (min) (c)	8	9.5	4	SIG WAVE HT (m)	0	0
THICKNESS (m)	1.4	1.4	1.4	TEMP (max) (c)	14		13	SIG SWELL HT (m)	0	0
DRIFT (kts)	0.39	0.65	0.50	WINDCHILL (c)			-9	MAX COMBINED (	0	0
DIR (deg)	104	110	105	SS TEMP (c)	0.6	0.4		TRACE		0
RIDGING ?(y/n)	Y	Y	Y	WIND DIR (deg)	220	210	250	WATER DEPTH (m)	30.0	30.0
ICE PRESS ? (y/n)	N	N	N	WIND SPEED (kts)	4 - 22	22	15 - 25	VISIBILITY (nm)	1.0	4.00

ENVIRONMENTAL SUMMARY:

Soutwest to south-southwest winds 4 to 22 knots, with extensive periods of fog.
Presently 4-5/10th ice cover, with little or no change expected today.
Ice recce flown August 1, 1993. See attached map.

M. Helmer BV8 R. Shields
L. Johnson BV8 E. Fercho
G. Pidcock BV8 G. Matheso

	ON HIRE									READINESS	Y/N	DECK CARGO/COMMENTS
I	95% C	1425	291.0	0	0	0	0	0	0	ANCHORING	Y	Misc. anchor equipment.
K	REC.	0	0	0	0	5.3	0	0	0	TOWING	Y	Ice support operations
A	DIS.	0	0	0	0	0	0	0	0	ICE MGMT	Y	Working bouy pattern out to 6 miles.
L	USED	23.0	0	0	0	3.0	0	.5	0	RECON	Y	
U	R.O.B	781.0	268.0	0	0	64.4	0	21.5	0	FUEL	Y	
K	S/U									DW	Y	
	ON HIRE									BULK	Y	
K	95% C	1425	343	0	0	0	0			ANCHORING	Y	Misc. anchor equipment.
I	REC.	0	0	0	0	7.0	0	0	0	TOWING	Y	Ice support operations.
G	DIS.	0	0	0	0	0	0	0	0	ICE MGMT	Y	Working 6 miles out to 12 miles.
O	USED	33.0	0	0	0	5.0	0	.308	0	RECON	Y	
R	R.O.B	870.0	343.0	0	0	23.0	0	13.698	0	FUEL	Y	
I	S/U									DW	Y	
A	ON HIRE									BULK	Y	
K	95% C	1860	0	0	139.5	0	0			ANCHORING	Y	Misc. anchor equipment.
A	REC.	0	0	0	0	0	0	0	0	TOWING	Y	Ice support operations.
L	DIS.	0	0	0	0	0	0	0	0	ICE MGMT	Y	Working 12 mile range.
V	USED	59.4	0	0	0	5.0	0	.385	0	RECON	Y	
I	R.O.B	1,077.8	0	0	139.0	34.0	0	43.916	0	FUEL	Y	
K	S/U									DW	Y	
	ON HIRE									BULK	Y	
S	95% C	440	211.2	0	0	0	0			ANCHORING		Oil Spill Equipment.
U	REC.	0	0	0	0	3.0	0	0	0	TOWING		Ice support operations.
P	DIS.	0	0	0	0	0	0	0	0	ICE MGMT	Y	Working bouy pattern.
Z	USED	10.0	0	0	0	3.0	0	0	0	RECON	Y	
	R.O.B	207.0	187.0	0	0	52.9	0	6.085	0	FUEL	N/A	
	S/U									DW	N/A	
	ON HIRE									BULK	Y	

MOORING	1	2	3	4	5	6	7	8	9	10	11	12	GAS	Full	M/T
WIRE LGTH(m)	1,030	1,147	1,180	1,143	1,147	1,147	1,180	1,090	1,180	1,147	1,030	1,070	OXY	7	12
WIRE OUT (m)	868	0	868	933	0	833	820	0	831	838	0	905	ACE	23	2
RAR S/N	159A		156A	152A		113A	153A		144A	131A		168A	NIT		
RAR CODE	ILMN		MNOP	ILKO		JKLM	IKLO		IMNP	JKMN		IJNP	HYDR		
GROUND PEN.	20		20	20		20	20		20	20		20	FREON		
ANCHOR TYPE	20T SS		15T SP	20T SS		12T SP	20T SS		12T SP	20T SS		12T SP	PROP	3	2
ANCHOR S/N	#37		#39	#38		#13	#36		#09	#33		#10	HELIUM		
FLUKE L (deg)	32		32	32		32	32		32	32		32	ARGON		
BEARING(deg)	170		231	258		318	348		51	80		141	BLUE S	2	
PIGGY TYPE	N/A		N/A	N/A		N/A	N/A		N/A	N/A		N/A			
ANCHOR S/N	N/A		N/A	N/A		N/A	N/A		N/A	N/A		N/A			
FLUKE L (deg)	N/A		N/A	N/A		N/A	N/A		N/A	N/A		N/A			
CROWN PEN.	70		70	70		70	70		70	70		70			
BUOY	Buoy		Buoy	Buoy		Buoy	Buoy		Buoy	Buoy		Buoy			

Figure 3.3: (continued) The sections of the Canmar operations report which summarize the ice conditions, mooring system and ice management support at the time.

4.0 Load Data Assessment

4.1 General

This section of the report presents the new Kulluk load data, compares it with some of the information from the original full scale data base, then provides composite plots of the two data sets, combined. The basic intent of this assessment is to summarize the new load data in the form of scatter plots, and to demonstrate that it ties together with the original Kulluk information in a sensible manner. This assessment is by no means rigorous, but is considered to be sufficient to identify major trends and key features in the data. Some of the more "operational aspects" of the information that is contained in the Kulluk data base, such as the ice management support and alert status in-place at the time of each ice loading event, are discussed separately, in Section 6.

The original data base contained enough specifics to evaluate loads on the Kulluk within the context of different ice interaction scenarios. Because of this, a fairly scientific approach was taken in which loading trends were investigated for unbroken level ice and unbroken ridge conditions, and in managed ice that either "cleared around the vessel well" or did not (see Figure 4.1). This allowed scatter plots of the Kulluk load data to be developed for specific ice interaction scenarios, like those shown in Figures 2.5 and 2.6.

Since ice interaction details are not available for the new Kulluk event data, a more basic and perhaps more practical approach has been taken in this work. Here, measured loads have been evaluated primarily in relation to the type of pack ice regime in which vessel stationkeeping operations were being carried out. This approach provides a "common sense perspective" of the range of ice loads that should be expected in various pack ice regimes, each one of which, in real terms, is comprised of a complex mix of ice features. It is also compatible with the "information content" of the new Kulluk load event data, and addresses one of the three key questions posed earlier, namely:

- what load levels have been experienced, and should be expected, on moored vessels in different pack ice conditions ?

4.2 Load Levels

4.2.1 New Event Data

The new Kulluk load data is presented in Figure 4.2, where it is shown as a function of the type of pack ice regime in which the vessel was stationkeeping, for all of the events without ice pressure. This new data is a direct reflection of the load levels experienced in managed pack ice conditions, when the Kuluk was operating within the specified ice regimes, with ice management support. In order to better display each loading event, the data points have been artificially spread out around the integer (or code) values that depict a particular ice regime. This was done by adding a random value (between ± 0.5) to the ice regime integer, for each event. By spreading the data out in this manner, "vertical line plots" which display, yet mask, all of the data points are avoided. Since the pack ice regime integers are by no means an exact measure, there are no real implications to this approach, in practical terms. This type of data spreading has also been used to better display the information contained in many of the other plots given later in this report.

There is a considerable amount of scatter in the new load data that is shown in Figure 4.2. However, there is a clear trend towards increasing ice load levels with increasing pack ice severity, as one would expect. The following points should be noted, since they are implicit in the new Kulluk load event data.

- the loads are the result of "unknown interactions" with managed ice features within the specified pack ice regime and, as such, may have been caused by level, ridged or rubbled areas of managed first year ice, or by old ice fragments, if present

- the events may have involved good ice clearance around the Kulluk, tight ice situations with poor clearance, or impacts with larger managed ice fragments within the pack, but again, the specific type of interaction is not known for these events

- however, these load levels represent "the bottom line reality" in operational terms, since they are the composite result of the specific pack ice conditions encountered, the ice interaction behaviours experienced, and the effectiveness of the ice management support provided

Load events that were caused by ice pressure, which typically resulted in "higher" load levels, are not included in Figure 4.2. These pressure situations were infrequent and only occurred in near continuous pack ice conditions (ie: 9-9+/10ths, or in pack ice regimes 4, 9 and 10). Figure 4.3 shows the new Kulluk load data for ice pressure situations, plotted against ice thickness. A general trend towards higher load levels with increasing pack ice thickness is evident. It is interesting to note that even in thin ice under pressure, load levels can be higher than those in many of the events in the more severe pack ice regimes, without pressure.

The new Kulluk load data that is shown in Figures 4.2 and 4.3 comes from ice interaction events in different months and different years, and hence, in different ice strength and friction conditions. Where relevant, corrections (or normalizations) in measured load levels should be made to account for variations in these ice properties. Because the pack ice that interacted with the Kulluk was prebroken by support icebreakers before causing the measured loads, no "correction" for ice strength is considered necessary. However, it seems reasonable to adjust the Kulluk load data to account for differences in ice friction, particularly in view of the following factors:

- the main ice interaction behaviour during the new load events involved "ice flow" around the Kulluk's hull, where ice friction is an important parameter
- the load events occurred across a wide range of ice temperatures

A procedure that was used in the original data base development work was applied to make the friction related adjustment to the new load event data. This procedure is based on one of the correction terms in an empirically based vessel resistance prediction formula (Keinonen et al, 1996). It indicates:

- friction influence on load is proportional to $1- 0.0083\ (T + 30)$

  where: T = ice surface or air temperature (in °C)

Air temperature, which is an entry in the data base, was used to normalize the new load data to - 10°C on this basis, to account for variations in ice friction. Figures 4.4 and 4.5 show the new Kulluk load data, for both “normal” and pressured ice situations, with this adjustment made. It may be seen that the normalized load event data “moves around a little” because of this correction, but the overall trends and load levels are not substantively different.
In Figure 4.4, an upper bound curve has been fit to the normalized load data, for all of the new Kulluk events without ice pressure. This bound was obtained by calculating mean and standard deviation values for the loads in each pack ice regime category, determining a “bounding value” for these categories at the mean plus two standard deviation level (the 95.5% non-exceedence level), then fitting a curve to these values with a regression analysis. This curve is intended to provide a reasonable upper bound to the new Kulluk load data that recognizes its intrinsic scatter, is not overly conservative, and is statistically based.

The trendline in Figure 4.5 is more straightforward. It is simply a curve that has been fit through the individual load data points for the new events involving ice pressure, which are limited in number. The lines in these two figures highlight the bounds and trends in the new Kulluk load data for normal and pressured ice interaction events, respectively.

4.2.2 Comparison with Original Event Data

The new Kulluk event data, when presented in the form of scatter plots for loads in different pack ice regimes and pressure situations, shows logical trends. An obvious question to ask is “ how consistent is this new load data, and the trends it suggests, with the original full scale Kulluk data? ”. Since there is no reason to believe that either data set should show any significant differences, this question was addressed in a simple and straightforward manner, to obtain some comfort about the compatibilty of the two data sets.

Firstly, the type of upper bound and trend lines that were fit to the new Kulluk data, as shown in Figures 4.4 and 4.5, were also fit to the original load data. These lines are shown in Figures 4.6 and 4.7, overlaid on the new load event data, for normal and pressured ice situations. It is clear that the trends in the original and new load data sets are very similar.

A more direct comparison was also made between the new Kulluk data, for loading events without ice pressure, and “key formulations” obtained from the original data base. For the purposes of this comparison, load versus ice thickness bounds that were derived from the original data have been used. As shown in Figures 2.5 and 2.6, these are:

- for managed ice clearing well around the Kulluk: y = 38 x + 31
- for “tight” managed ice that cleared poorly: y = 87 x + 91

where y = load (in tonnes)
x = ice thickness (in metres)

The results of this comparison are shown in Figure 4.8. It can be seen that the new Kulluk load data is scattered below the upper bound line, which describes expected peak load levels in tight managed ice with poor clearance. Many of the data points are also either close to or below the “lower” bounding line, which describes interaction situations involving managed ice with good clearance. This result is by no means surprising and reinforces the compatibility of the two data sets. Although the type of ice interaction that was associated with each new loading event is not known, it is likely that the higher load levels reflect poor ice clearance situations, and the lower load levels reflect those with good ice clearance.

4.2.3 Combined Event Data

To this point, the new Kulluk load event data has been presented, and its compatibility with the load information in the original data base demonstrated. Because the two data sets are actually “one in the same”, they have been combined, and are used in this composite form throughout the remainder of this report.

The combined Kulluk load event data is shown in Figure 4.9, where it is plotted as a function of pack ice regime , for situations in which ice pressure was not experienced. An upper bound curve to the load data is also provided. Again, this curve has been developed by calculating mean and standard deviation values for each “pack ice regime bin”, then computing a best fit curve through the mean plus plus two standard deviation values for each bin (ie: the 95.5% non-exceedence level).

Figure 4.10 shows the combined Kulluk load data for events involving ice pressure, plotted as a function of ice thickness. All of these pressure events were (necessarily) seen in a near continuous pack ice cover and as such, their occurrences were limited to pack ice regimes 4, 9 and 10. A trendline has been fit through these data points, along with a reasonable upper bound. The trendline is simply a best fit curve to the load data, while the upper bound was more pragmatically established, by shifting this trendline upwards by 75%.

These two plots, which combine the the new and original load event data, represent one of the key results of this study, inasmuch as they summarize full scale loads on the Kulluk in a wide range of managed pack ice conditions. With reference to these load plots, the following points should be noted:

- Figure 4.9 provides Kulluk load data for more than 600 ice interaction events, in various pack ice regimes, without ice pressure.

  - this load data spans hundreds of days of operations, over a seven year period
  - compositely, it reflects all of the ice interaction situations seen in managed pack ice, ranging from those with good ice clearance, to those with poor ice clearance, to occasional impacts with sizable floe fragments
  - the load levels are not particularly high for all but the thicker, higher concentration pack ice regimes
  - even in these heavy pack ice conditions, load levels are less than 400 tonnes
  - this is quite remarkable when one recognizes the significant potential for much higher loads, should the effectiveness of the Kulluk's ice management support system and/or other in-ice operating procedures have broken down
  - here, it is also important to appreciate that on a few occasions, there were severe ice features which could not be effectively managed
  - had these severe features impacted the Kulluk prior to a move off location, load levels would have been far in excess of 400 tonnes
  - the four outlying load points that are circled in Figure 4.9 are symptomatic of this, since they were caused by "large floe" impacts in fairly low pack ice concentration situations, where the ice was poorly managed
  - two other load events have been excluded from this plot, since they resulted from

mistakes made onboard the Kulluk, and are not representative

- the first involved an impact with a rough unmanaged first year ice floe during the first week of Kulluk operations in the Beaufort Sea. The floe was about 1.5 km in size, 2m in mean thickness, had ridges, and was in a 2/10th ice concentration area. This event resulted in a peak load of 601 tonnes.
- the second "blatantly stupid" event occurred about a month later. In this case, an "unmanageable" multi-year floe, 10-15 km in size, 5m in thickness, with 20-30m ridges was allowed to impact the Kulluk at 0.6 m/sec. Load levels quickly approached 2000 tonnes before mooring lines broke, and it was pushed off.

• The load data that is presented in Figure 4.10 contains more than 50 events in which the Kulluk experienced ice pressure.

- most of these pressure events occurred in the freeze-up/early winter period, when the ice was 0.3m - 0.7m in thickness and near continuous (ie: 9+/10ths)
- however, there are also a few events in heavy spring and summer ice conditions, comprised of substantially thicker pack ice
- the load levels shown are relatively high, up to several hundred tonnes or more, even in thin ice
- in some of these cases, the Kulluk moved off, since load levels were increasing
- as a result, this load data is not necessarily indicative of a true upper bound
- in the Beaufort Sea, ice pressure occurrences were innocuous, and the onset of these events was difficult to predict
- ice management was not effective in reducing load levels in heavy ice pressure situations and often gave rise to the formation of thicker ice rubble around the Kulluk, which exacerbated the problem
- ice pressure occurrences are not expected during pack ice intrusions onto the Grand Banks, because of the relatively "loose" nature of the pack and the "overall openness" of the area. Hence, load analogies with (or extrapolations from) the ice pressure event data in Figure 4.10 are not relevant.
- for ice infested waters like those off Sakhalin Island or in the Pechora Sea, where ice pressure events are more common, this information is of higher importance

4.3 Related Comments

Some might suggest that the Kulluk load event data, when presented as a function of the type of pack ice regime in which vessel stationkeeping operations were being carried out, is an oversimplification. Often, there is a tendency to define extreme ice features within the ice regime of interest and, for floating systems, to try to design a mooring system that is capable of withstanding the loads they may impose. This is an obvious and well established approach for the design of fixed structures in ice, and for the design of floating systems in "singular situations" such as the extreme storm wave event. However, defining "black and white ice criteria" for floating systems tends to become problematic, particularly when ice management and other mitigative measures (eg: moving-off location) are part of the operating philosophy. The Kulluk is a prime example in this regard. Its mooring system was originally designed to withstand the load from 1.2m of level unbroken ice, in a stationkeeping mode, within small offset tolerances. However, the vessel successfully operated in much more severe pack ice conditions, with ice management support, and with the ability to "quickly disconnect" from its mooring should an adverse ice situation arise. If, for example, a fairly common "extreme ice feature" like a 15m thick first year pressure ridge had been selected for the Kulluk's design, its mooring capacity requirement would have been in the order of a few thousand tonnes. In turn, the design of a practical mooring system would not have been possible, and the Kulluk would have never been built, nor its in-ice operations attempted.

Since Beaufort Sea ice conditions and their variations span a wide range of pack ice regimes, reasonable analogies can be drawn with ice conditions in other areas, based on experience and judgement. For example:

- the Grand Banks pack ice cover, when present, generally consists of thin ice types and small ice floes, similar to those characterized by pack ice regime 4 in Figure 4.9. In this type of pack ice situation, expected ice load levels are relatively low.

- off Sakhalin Island, where the winter pack ice cover contains thick and heavily deformed first year ice areas, conditions like those reflected in pack ice regimes 9 and 10 are more relevant. Here, ice load levels can be relatively high, particularly when ice pressure events are considered.

Means of applying the Kulluk data to estimate expected load level on floating systems in pack ice conditions like those found on the Grand Banks and off Sakhalin Island are outlined later, from the perspective of both pack ice regimes and specific design ice features.

However, before proceeding to this point, it is worthwhile reviewing the key elements of the ice management system that was used to support Kulluk operations, and reduce load levels. It is also important to obtain some feel for the effect of different levels of ice management support, along with some perspectives relating to operational risk (ie: alert status). These areas are discussed in the next two sections of this report, to address the following question.

- what types of ice management activities have been used to reduce the ice load levels on moored vessels in pack ice, and to mitigate risk ?

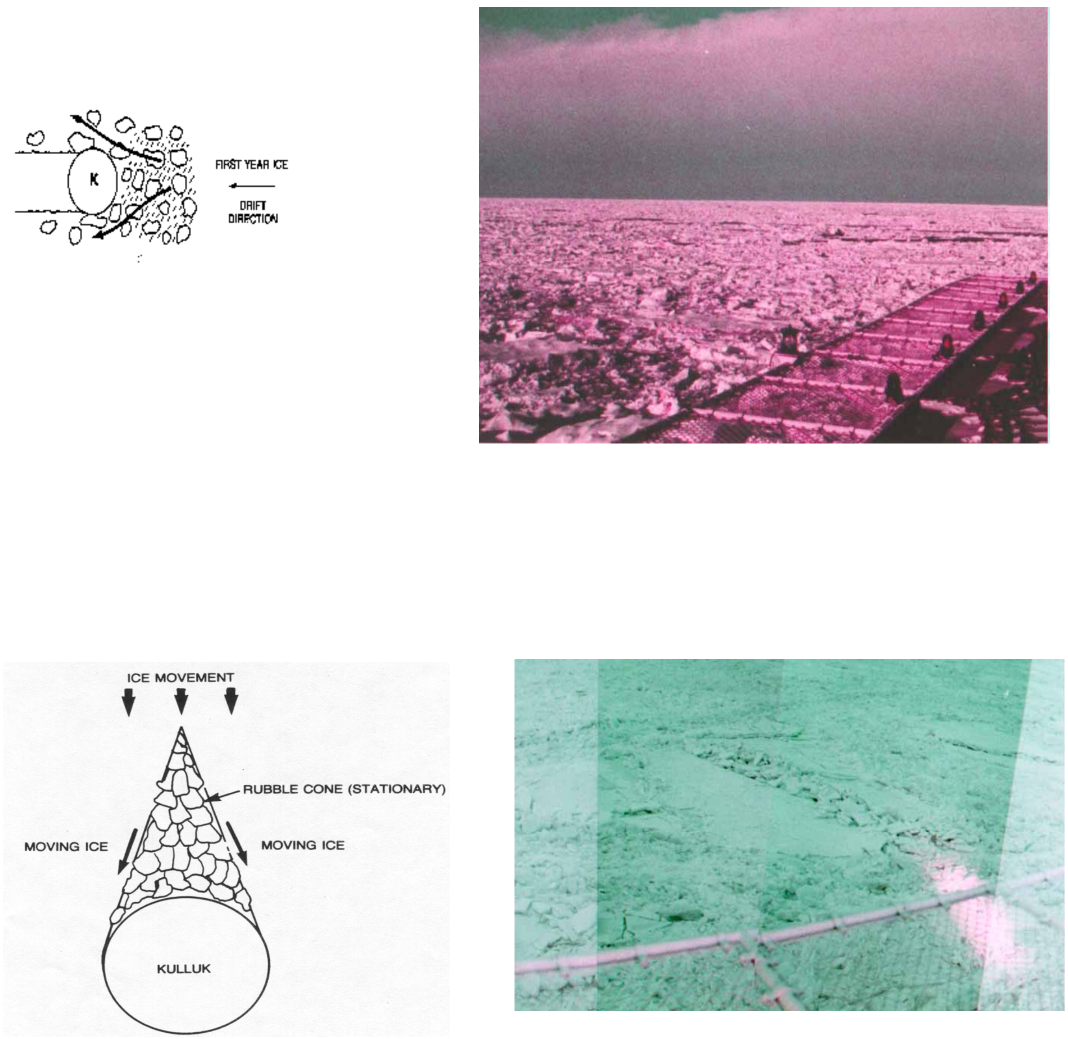


Figure 4.1: This figure illustrates situations involving the "good and poor" clearance of managed ice fragments around the Kulluk. The upper part of the figure shows ice clearing well, as a slurry. This clearance behaviour was associated with low ice load levels. The lower part of the figure shows poor clearance situations, in which a rubble wedge would form on the updrift face of the Kulluk, causing higher load levels.

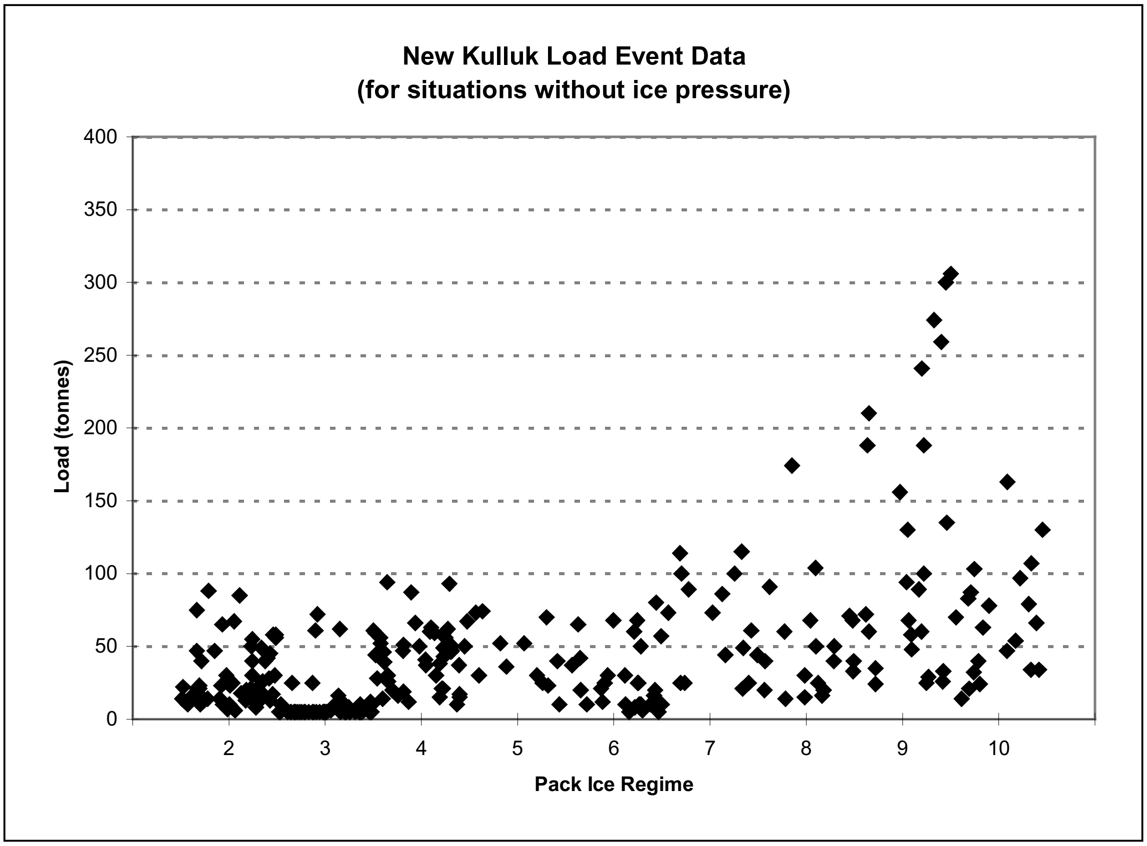


Figure 4.2: New Kulluk load event data, shown as a function of the pack ice regime in which the vessel was operating. Regimes 9 & 10 represent 9-9+/10ths of medium to heavy pack ice conditions. Regimes 7 & 8, 5 & 6, and 2 & 3 represent medium to heavy pack ice areas with mean concentrations of 8/10ths, 5/10ths and 2/10ths, respectively. Pack ice regime 4 covers near continuous thin ice during fall and early winter.

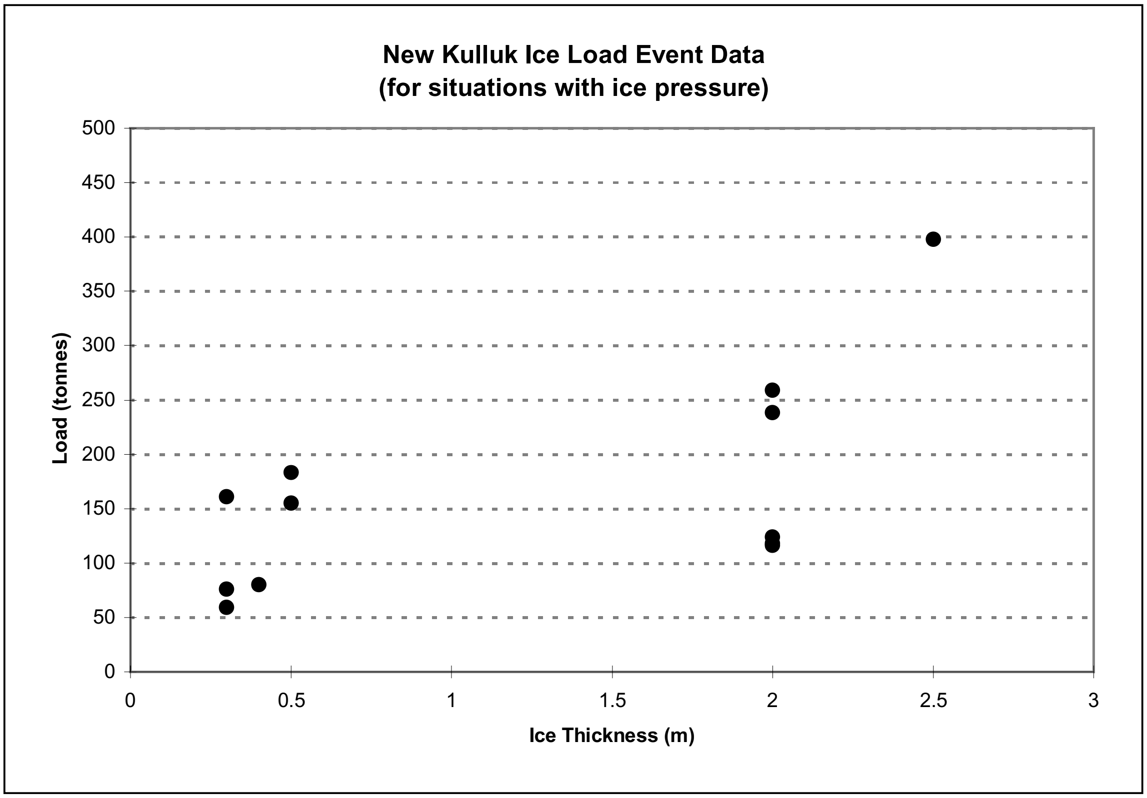


Figure 4.3: New Kulluk load event data, for situations involving ice pressure.

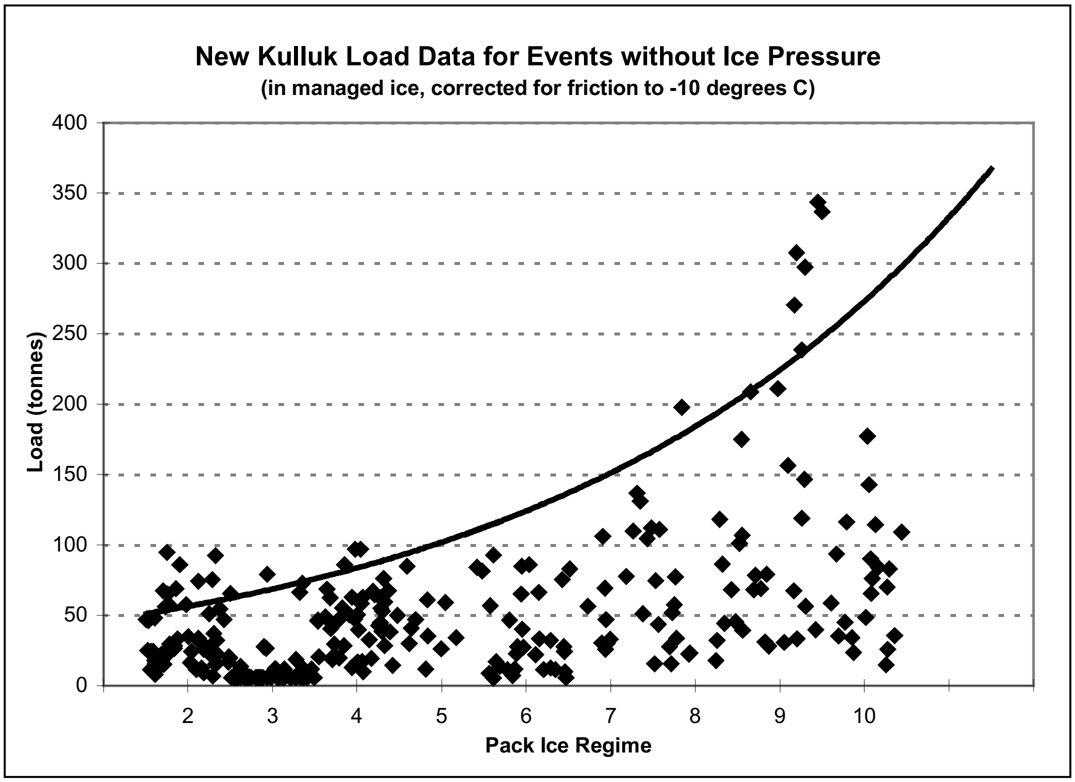


Figure 4.4: New Kulluk load event data, shown as a function of the pack ice regime in which the vessel was operating. This data has been normalized to account for variations in ice friction, to - 10°C. A reasonable upper bound has also been fit to the load data, at a 95.5% non-exceedence level. This bounding line is described by $y = 38\ e^{0.2x}$.

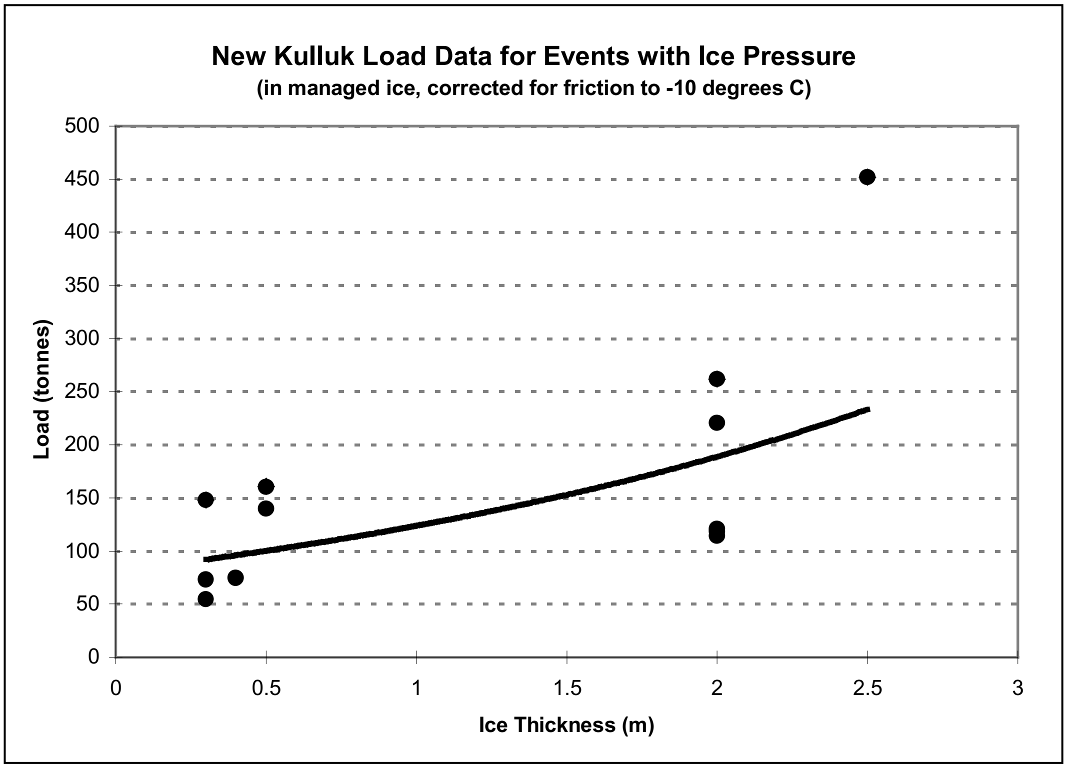


Figure 4.5: New Kulluk load event data, for situations involving ice pressure, also normalized to account for variations in friction. A simple trendline has been fit through this data, which is described by $y = 81\ e^{0.42x}$.

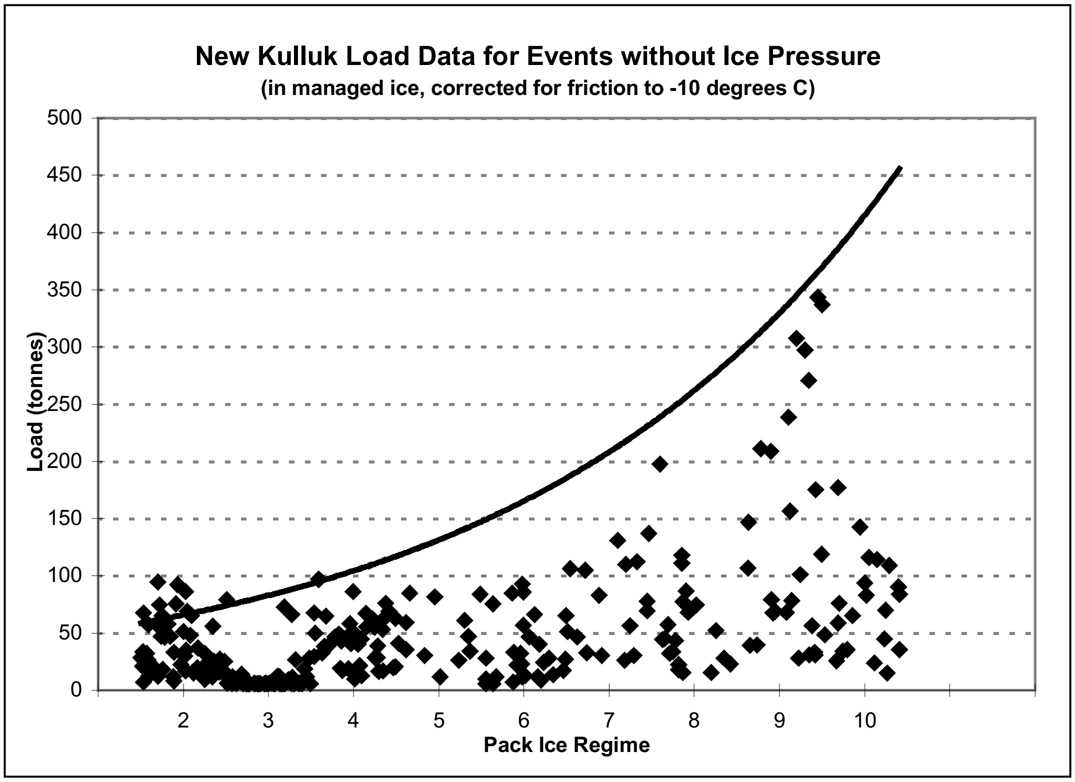


Figure 4.6: The new Kulluk load event data, normalized for friction, as a function of pack ice regime, with the 95.5% non-exceedence bounding curve for the orginal data superimposed upon it. The bounding line for the original data set is described by $y = 41.6\ e^{0.23x}$. It is clear that the new and original data sets are compatible.

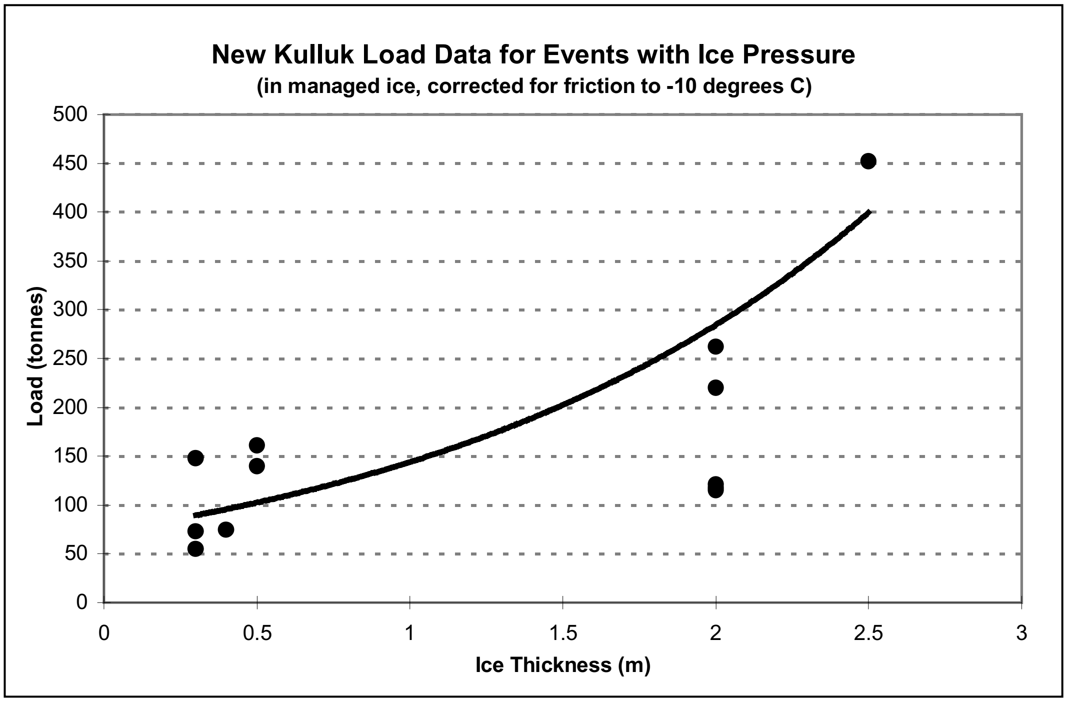


Figure 4.7: New Kulluk load data for ice pressure situations, normalized for friction, with the trendline for pressure events in the original data set superimposed upon it. This curve, which is described by $y = 73\ e^{0.68x}$, again illustrates the compatibility of the new and original load data sets.

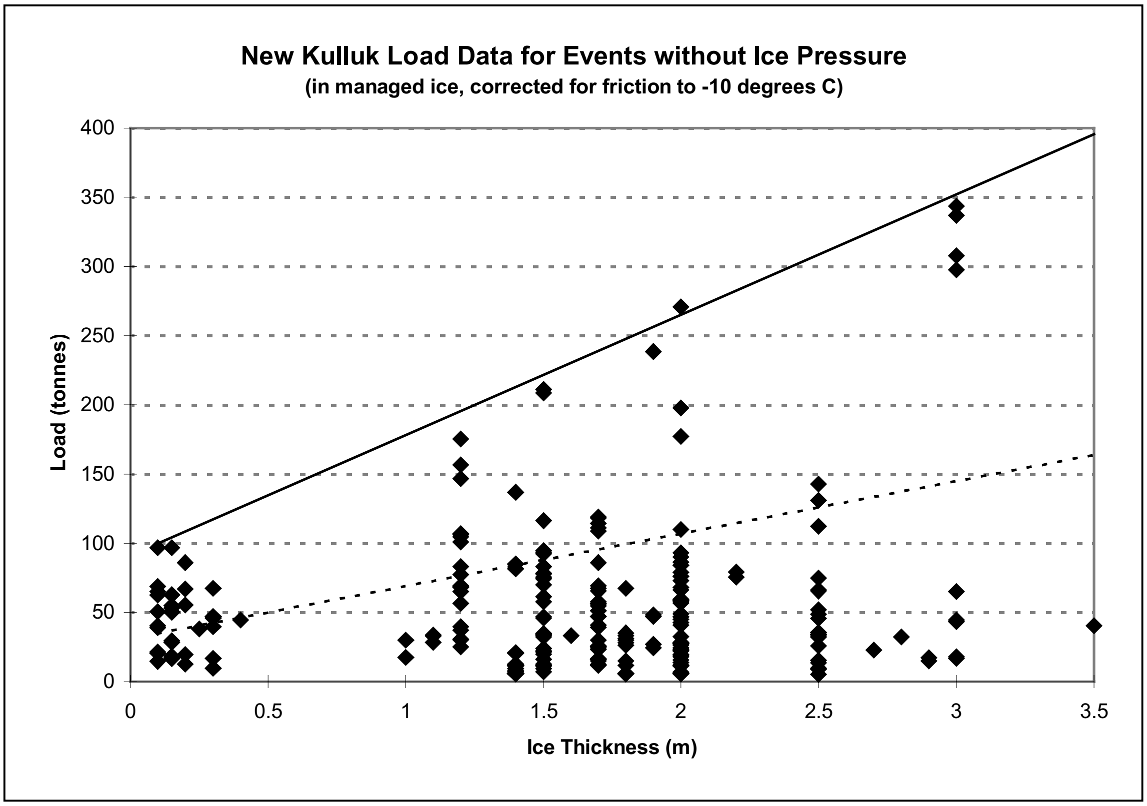


Figure 4.8: The new Kulluk load data, plotted as a function of managed ice thickness, for all events without ice pressure. Again, this load data has been normalized to account for variations in ice friction.The two bounding lines that are shown were derived from the original load data base, for ice interaction situations with good and poor clearance of managed ice fragments around the Kulluk. One would expect most of the new Kulluk load data points to fall below these lines, since they represent bounds at the 95.5% non-exceedence level. It can be seen that they do, which reinforces the compatibility of both data sets.

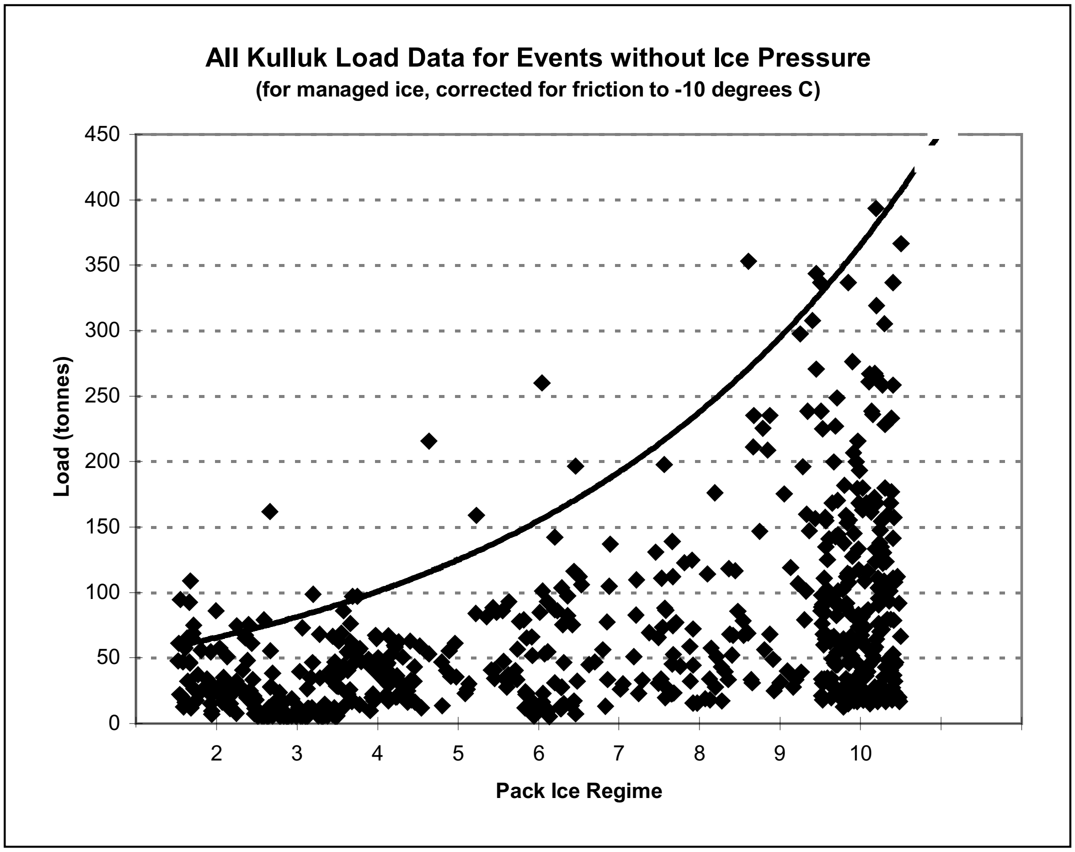


Figure 4.9: All of the Kulluk load data combined, normalized for friction, as a function of pack ice regime, for events without ice pressure. A bounding curve has also been fit to this combined load event data at the 95.5% non-exceedence level. This curve is described by $y = 42.7\ e^{0.21x}$. It is interesting to note that four of the outlying points (the ones that have been circled) were caused by impacts from large thick ice floe fragments that had not been well managed.

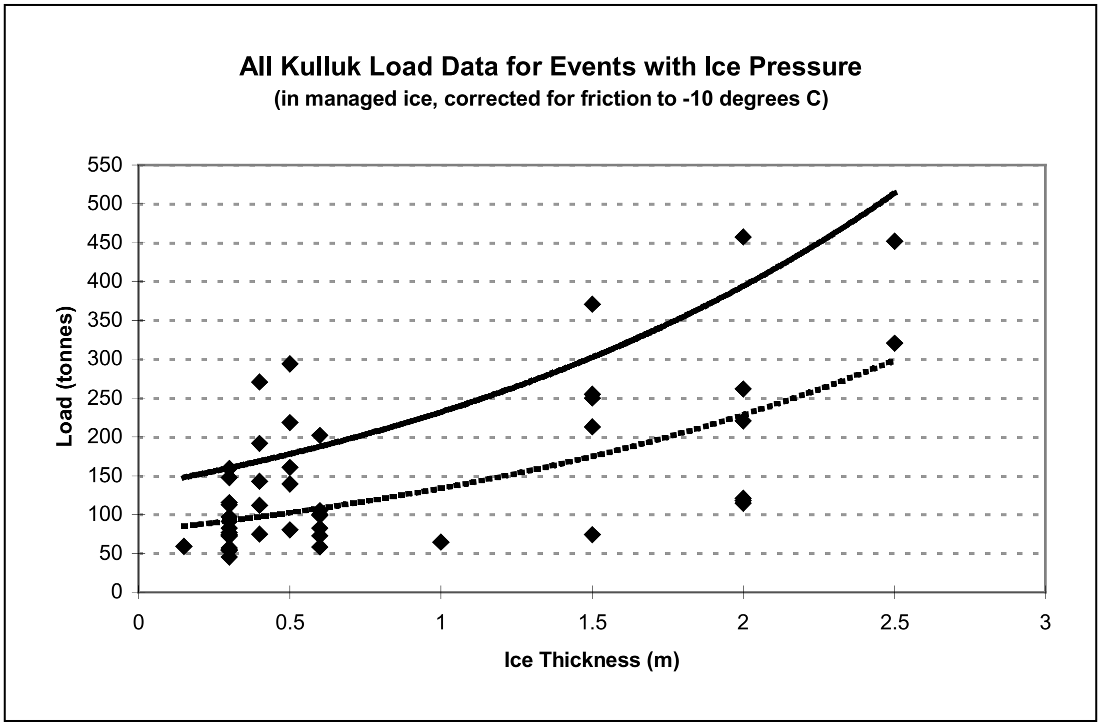


Figure 4.10: All of the Kulluk load data combined, and normalized for friction, for ice pressure events. The mean trendline through the load data points is described by $y = 78\ e^{0.53x}$. The crude upper bound that is shown was simply computed by shifting the mean trendline upwards, by 75% (ie: $y = 136.5\ e^{0.53x}$).

5.0 Ice Management Systems

5.1 General

In this section of the report, some of the key ice management activities that were used to support Kulluk stationkeeping operations in Beaufort Sea pack ice are highlighted. As noted earlier, ice management was required to reduce ice load levels on the Kulluk and made a very important contribution to the success of its operations, particularly in terms of safety and efficiency.

For the purposes of this report, the Kulluk's ice management systems are considered in an all inclusive way, rather than only addressing the types of icebreaker support activities that were involved. This is in keeping with the way ice management systems are defined in the context of operations on the Grand Banks, by industry, by the regulators, and by other groups such as C-CORE.

The basic components of the Kulluk's overall ice management system included:

- an ice monitoring & forecasting system
- a performance monitoring system
- an ice alert system
- an icebreaker support system
- well defined operating procedures
- well defined lines of communication, responsibility and authority

The need for these system components, and the manner in which they were used, followed the basic logic framework shown in Figure 5.1. This logic should be clear and in fact, quite obvious, since it simply represents a stepwise rationale for prudent operations in continually changing pack ice situations. It is by no means unique, nor fundamentally different from the approach taken by operators on the Grand Banks for many years, in support of their drilling activities in bergy waters. More recently, this basic "in-ice operating philosophy" has been applied to floating system operations in spring pack ice conditions off Sakhalin Island, with good success (Keinonen et al, 2000).

5.2 Ice Monitoring & Forecasting

A sound knowledge of the actual and expected pack ice conditions, on both regional and local scales, was an essential front-end component of the Kulluk's ice management system. As shown in Figure 5.1, this information was the first key input to strategic and tactical planning, including the level and type of ice management that was provided by support icebreakers. Having a good ice monitoring and forecasting capability was also a well defined regulatory requirement for most offshore operations in the Beaufort Sea, as it is on the Grand Banks, and elsewhere.

The primary objective of the Kulluk's ice monitoring system was to identify all potentially hazardous ice conditions, features and situations that could adversely impact stationkeeping operations. This had to be done with sufficient reliability and timeliness to provide adequate warning, so that appropriate response actions could be taken. These actions ranged from the use of ice management vessels, through an orderly shut-down of drilling operations, to a move-off location, if required. The system also had to provide a "continuous" ice surveillance capability, during summer and winter, day and night, and through all types of weather and visibility conditions.

The ice monitoring and forecasting system was comprised of a variety of components, which included:

- some of the publically available services provided by the Canadian government
- industry funded regional services that were jointly shared by Beaufort operators
- site-specific services provided by Gulf Canada, who operated the Kulluk

Clearly, there are strong analogies between this cooperative data acquisition approach and the joint arrangements that various operators are now using to monitor and forecast iceberg and pack ice conditions on the Grand Banks. In this regard, the only comment to make is that a "shared, coordinated and well thought out system" makes very good sense in terms of the synergies and cost efficiencies it can provide.

The basic elements of the Kulluk's ice monitoring and forecasting system are highlighted as follows. More specific details about the system have been given elsewhere (eg: Dixit et al, 1985), and will not be repeated here.

Local Ice Information	- distance scales of a few hundred metres to 10-15 km from the Kulluk, primarily updrift - time scales of tens of minutes to a few hours
- ice concentration, types, thicknesses, ridging, floe sizes	- onboard ice observers (visual estimates - hourly) - occasional helicopter recces - support icebreaker reports
- local drift speed & direction	- marine radar (sequential fixes - hourly, or more frequently if required - support icebreaker "fixes" and reports
- character & "manageability" of the ice	- support icebreaker reports
- ice drift forecasts	- simple onboard forecast models - most often "nowcasts" and persistence tracking
- information synthesis, ice hazard identification & advise	- onboard ice advisor
Regional Ice Information	- distance scales of tens of km to 100 km, or more - time scales of a day to a few days
- regional pack ice distribution & characteristics	- periodic airborne radar (SAR or SLAR) flights downlinked to the Kulluk - as available satellite imagery
- regional pack ice movements	- sequential fixes of "resolvable" ice features, edges - drift buoys placed on the pack ice
- regional ice drift forecasts	- fairly basic models, coupled with wind forecasts

- ice information from other locations - cooperation & data exchange with other operators

Ice information needs and the manner in which they are satisfied will have similar elements to this "Kulluk system summary", on the Grand Banks and in other areas that are subject to pack ice. Obviously, icebergs and small ice masses are additional factors of concern for the Grand Banks region.

Here, there is little point in saying too much more about the ice monitoring and forecasting systems used to support Kulluk operations. In addition, technology has come a long way since the Kulluk last worked in 1993, and new and improved methods are now available to meet various ice information needs. One example is RadarSat and its SAR, and the all weather, high resolution, large area ice imagery it provides. Despite these comments, the following observations may be of some use, based on past experiences with the Kulluk.

- "high resolution" ice detection and monitoring in poor visibility and darkness conditions is an important requirement and was a challenge in the Beaufort, as it will be on the Grand Banks and in other areas. High waves, sea spray and various forms of precipitation are additional complications on the East Coast.
- identifying small old floes in rough first year pack ice was not always easy. There are similar concerns on the Grand Banks, for any small glacial ice masses or old ice floe fragments that may be contained in the pack. (These features are probably more hazardous to support vessels than to an ice capable FPSO, for example)
- although remotely sensed ice information is an essential ingredient of any system, there is nothing like an "experienced eyeball" to view and assess an ice situation. In this regard, the timely availability of a helicopter for local reconnaissance is of high importance.
- ship reports of ice conditions and their manageability are a key input. However, support vessel personnel do not always have the same perspective of hazards and time frames as those responsible for moored vessel operations. Education, good communication and well defined procedures are key factors in this regard.
- ice information that is not timely is virtually useless. Similarly, if any ice input lacks reliabilty, it will only be used once or twice before it is viewed as potentially misleading, and of little value. Local ice movement forecasts in the Beaufort Sea and iceberg trajectory predictions on the Grand Banks are prime examples.

- a lot of regional detail about the ice is not important, whereas local detail is
- any systems that are used for ice monitoring and forecasting should be proven, practical and cost effective. "Piggy-backed" R&D is often warranted, but should be identified as such, and not "sold" as proven.

5.3 Performance Monitoring

Performance monitoring was also a key ingredient of the Kulluk's overall ice management system, in terms of the manner in which it became focused and was subsequently operated. When the Kulluk was orginally conceived, the design target was to allow drilling operations in level first year ice to 1.2m in thickness, as noted earlier. Although this "operating limit" was well defined on the basis of model tests and other analyses, it was recognized as being less than realistic, given the icebreaker support that would be provided, and the nature of Beaufort Sea pack ice itself.

Performance monitoring of the Kulluk was driven by several objectives and needs. These are briefly highlighted as follows, along with some background as to how the system evolved.

- the Kulluk was a novel concept, and was the first moored vessel designed with the intent of stationkeeping in a broad range of moving pack ice conditions. Because of this, there were many unknowns about the ice load levels it would experience, the manner in which it would perform, and the effects that icebreaker support would have. Accordingly, there was a desire to obtain quantitative information in these areas, in full scale, with a view to:

    - establishing realistic performance capabilities and limits for the vessel and its support icebreaker system in different pack ice situations
    - increasing the knowledge base for future floating system designs

- in terms of basic operations, there was a need to monitor individual mooring line lengths and tensions when anchors were being run and set, and to monitor Kulluk offsets and motions when drilling was underway. Due to "budget concerns", the construction group fostered the installation a rudimentary set of instruments to meet these needs, at low cost.

The rationale was that these instruments could be manually read onboard to obtain the necessary information, when operations were being carried out. They included:

- line length and line tension dial displays in separate winch houses
- analogue strip chart displays of the 12 individual line tensions in the control room
- level "bubbles" to look at pitch and roll levels at separate spots in the control room
- an acoustic positioning system (installed on the seafloor) for offsets, with a tabular readout in the control room

- as construction was nearing completion, personnel who would operate the Kulluk were being assembled. The operating philosophy adopted by this "operations group" was to monitor the behaviour of the Kulluk and its mooring system, in real time, but in a practical and usable way. The value of having "integrated, relevant and well displayed" real time performance information available to them was well known, from their past experiences. It was also considered necessary, as part of the basis for prudent operations.

- consequently, better performance monitoring systems were installed on the Kulluk, as it entered and began operating at its first location in the Beaufort Sea. The primary upgrades included a number of additional instruments, along with computerized data acquisition, recording and real time display systems. This "retrofit activity" was by no means easy, in an operational setting and under very tight time constraints. However, it was fortuitous, because "Murphy's law" brought heavy pack ice over the Kulluk's location a few days after it began drilling. The information provided by the system was invaluable, particularly in terms of quickly moving up the learning curve regarding ice loads, vessel responses, and the effects of ice management. It also had an immediate and positive impact on the safety and efficiency of the operation.

The Kulluk's performance monitoring system has been described elsewhere (Pilkington et al, 1986, Dixit et al, 1985), and specific details are not given here. However, in overview terms, its main components consisted of:

<u>Tensions & Global Loads</u>

- individual line tensions	- from strains measured in the turndown shives

	- calibrated by an onboard load application system
- global loads	- vectorial summation of individual line tensions

Vessel Response Motions

- offsets	- from a biaxial tiltmeter on the riser's base - (the acoustic positioning system never worked in ice, probably because of ice noise)
- heave & rotational motions	- from a heave measurement device & gyros

Data Recording & Display

- global load, line tension & motion recording	- real time chart record time series of the calculated and directly measured values - magnetic tapes of the same at 1 - 4 Hz
- real time information display	- a real time screen display of all relevant performance information referred to as the KATSASS (see Figure 5.2) - this display was refreshed every 1 second

It is likely that similar types of performance monitoring systems will (or at least should) be used on floating systems in other areas that are subject to ice, such as the Grand Banks. In this regard, it of interest that the Terra Nova group, with PERD support, is now pursuing means of measuring pack ice loads on their FPSO and its mooring.

5.4 Ice Alert Procedures

The Kulluk was used as a platform for drilling operations in the pack ice conditions common to the Beaufort Sea's break-up through early winter periods, with ice management support. However, extreme events such as unmanageable old ice floes or pressure situations sometimes required a temporary suspension of drilling activities on the Kulluk and, at times, a move-off location. Since many drilling operations required a number of hours to complete, the Kulluk's performance, and the ice conditions that could impact this performance, were continuously monitored as outlined above, and integrated into an ice alert system.

The purpose of this system was to define, in a timely manner, any hazards to the Kulluk/well that could cause an interruption to drilling operations or threaten the security of the well or vessel, so that appropriate response measures could be taken. Hazards were divided into the following types, for which both the hazard severity and the time available before its arrival determined the appropriate set of responses.

- ice conditions
- weather and wave conditions

The alert system included a sequential list of alert status colour codes, generally defined as shown in Figure 5.3. Although these colour codes were sequential, some events could occur more rapidly than predicted, in which case the alert status was allowed to bypass some levels, and a rapid response undertaken, as appropriate.

The ice alert criteria or hazards were based on the performance limits of the Kulluk and its mooring system, with ice management support. Limiting ice conditions for stationkeeping, while drilling, were those which had the potential to:

- cause global loads in excess of the Kulluk's mooring capacity, and excessive offsets over the wellhead (ie: more than 5% of water depth, typically 1m - 3m)

- cause tensions in excess of 50% of the breaking strength (260 tonnes) in individual mooring lines

Actual and expected ice conditions, the performance of the icebreaking support vessels, and the Kulluk's expected response to the oncoming ice were all continuously monitored within the alert system. This included a continuous watch by the marine staff and ice advisor onboard the Kulluk. Two time factors were relevant.

<u>ST - Secure Time</u>

The time required to secure and disconnect from the well, so that the Kulluk was in a position to quickly adjust (stream out) its mooring and leave the site, if necessary. Estimates of ST included adequate safety margins to ensure the well could be properly secured in an orderly manner, and an additional time factor (about 2 hours) to accommodate an orderly mooring disconnect and move-off sequence. The securing procedure depended on the well condition but secure times were typically in the order of 4 to 6 hours. It is interesting to note that the Kulluk's ST time frames are in the same range as those cited for the Terra Nova FPSO.

HT - Hazard Time

The estimated time before the arrival of hazardous ice condition(s), which could exceed the operating capability of the Kulluk in a drilling mode.

The difference between HT and ST determined the amount of time that was available before a particular response must begin. For example, if an old unmanageable ice floe was expected in 12 hours and it required 6 hours to properly secure the well and move-off, then:

HT - ST = 12 hours - 6 hours = 6 hours

A yellow alert would then be entered into, with six hours available to continue any drilling operations. When the ice floe was within 6 hours of anticipated contact with the Kulluk and, assuming that ice management had not been successful, then:

HT - ST = 6 hours - 6 hours = 0 hours

and a red alert was declared, and well securing procedures began.

The ice alert status, and changes to it, prompted a variety of very specific, integrated and well defined response actions. These ranged from an increased frequency of ice observations, to the provision of more icebreaker support on site, to higher levels of communication between the Kulluk and icebreakers about ice management strategies and their effectiveness. Clearly, it was critical that the decision making and response guideline set out in the alert system were systematically followed. Otherwise, the possibility of poor and/or uninformed judgements by individuals had the potential to significantly increase operational risk.

Implementation of the ice alert system was the responsibility of the Kulluk's OIM (Offshore Installation Manager). However, the Marine Superintendent, supported by the Ice Advisor and the Drilling Superintendent, had the key functional responsibilities. In this regard, clearly defined roles, accountabilities and lines of communication were a key part of the alert system.

By way of summary, the importance of the alert component of the Kulluk's ice management system cannot be overstressed. Clearly, alert procedures should be a key part of any floating system operations in ice, in terms of identifying, dealing with, and mitigating ice-related risks. Operators on the Grand Banks are well aware of these types of ice alert procedures and have used them for years. New "in-ice operators", like those now developing oil and gas fields off Sakhalin Island, have also learned about them and have incorporated these procedures into their floating system operations,with good success (Keinonen et al, 2000).

5.5Icebreaker Support

In most pack ice conditions, icebreaker support was required to fragment the oncoming pack ice cover, to reduce load levels on the Kulluk. This activity was the "central element" of the Kulluk's ice management system. It was also the primary factor in terms of keeping ice load levels within acceptable bounds and, in turn, contributing to safe and efficient stationkeeping operations.

One of the objectives of this report is to highlight the ice management techniques that were used to reduce ice load levels on the Kulluk, on the basis of first hand experience. This is not a straightforward consideration because, in a practical sense, each ice management situation had different specifics and certain elements of uniqueness. In this regard, there were a wide range of factors that influenced ice management activities, and the relative effectiveness of these activities. They include:

- ice concentrations, types, thicknesses and roughnesses
- ice drift speed and changes in ice drift direction
- floe sizes, and the degree of "looseness or tightness" in the ice cover
- the strength of the pack ice, and specific features within it

- the occurrence of and severity of pressure (convergence) in the pack
- visbility levels (eg: long daylight hours vs fog, blowing snow, polar darkness)

A few simple "summary comments" that are related to these factors are given as follows.

- as ice concentrations, thicknesses and drift speeds increased, the icebreaking vessels had to deal with more pack ice on a unit time basis, and ice management became increasingly more challenging

- changing ice drift direction situations, which typically involved some uncertainty about the degree and rate of drift direction change, required more icebreaking updrift of the Kulluk, to create a "comfortable managed ice swath width"

- as the number of heavy ice features (eg: large ridges, rubble fields) increased, the amount of ice that could be broken per unit time decreased, because the repeated ramming that was needed to fragment them took time and "tied up" icebreaking resources
- as the pack ice became heavier and tighter, and in pressure situations, manoeuvring and turning the support icebreakers became more difficult, and the ice management process slowed significantly

- poor visibility and darkness was an important factor in slowing icebreaking activities, and being comfortable the ice had been adequately managed, moreso in thick heavy ice than in thin ice conditions

The icebreakers that were used to provide ice management support for the Kulluk were very capable and in fact, the operation was somewhat "spoiled" in this regard. These icebreaking vessels were the Terry Fox, the Kalvik, the Ikaluk and the Miscaroo, whose particulars are summarized in Table 5.1. Because they supported all of Gulf's Beaufort Sea operations, they were by no means exclusively dedicated to ice management at the Kulluk. Typically, two or three of these icebreakers were present around the Kulluk in heavy pack ice conditions. In terms of their icebreaking performance, the following points should be noted.

- the Terry Fox and Kalvik were the larger, more highly powered icebreakers and could break cold first year ice that was 1.6m thick continuously, at about 3 knots. The same limit for the Ikaluk and Miscaroo was 1.2m.

- in “real” pack ice conditions ((ie: not an ideal continuous level ice sheet), the following ranges of icebreaking transit speeds were fairly typical. These are only approximate, but provide some feel for the speed of “ice management”.

	Fox/Kalvik	*Ikaluk/Miscaroo*
thick pack (ice regimes 7 - 10)		
- cold (spring & fall)	5 - 7 knots	4 - 6 knots
- warm (summer)	8 - 10 knots	7 - 9 knots
thin pack (ice regime 4)		
- cold (fall & early winter)	10 - 12 knots	8 - 10 knots

- when there was significant pressure in the pack ice, whether it was thick or thin, transit speeds slowed to several knots and turning became more difficult, as noted above

Table 5.1: Brief Overview of the icebreakers used to support the Kulluk

Particulars	Terry Fox, Kalvik	Ikaluk, Miscaroo
Dimensions		
Length	88.0 m	78.8 m
Breadth Extreme	17.8 m	17.2 m
Depth Molded	10.0 m to main deck	9.7 m to main deck
Operating Draft	8 m	7.5 m
Engine		
Power	23,200 hp (17,300 kW)	14,900 hp (11,110 kW)
Main Engine	4 x Stork Werkspoor Diesel	4 x Wartsila Diesel
Thrusters Fwd.	Twin Air Bubbler System 777,000cf/hr (22,000m^3/hr) each	Omnithruster System 1200 hp (895 kW)
Thrusters Aft.	1 x 500 hp (373 kW)	1 x 800 hp (596 kW)
Water Maker	94 bbls/day (15 m^3/day)	63 bbls/day (10 m^3/day)
Bollard Pull	Over 220 tons (200 tonnes)	165 tons (150 tonnes)
Service Speed		
Two engines	13.4 knots in open water	12.0 knots in open water
Four engines	15.4 knots in open water 3 knots in 1.6 m of ice	14.7 knots in open water 3 knots in 1.2 m of ice
Fuel Consumption		
Open water	189 bbls/day (30 m^3/day)	126 bbls/day (20 m^3/day)
Heavy ice	314 to 472 bbls/day (50 to 75 m^3/day)	220 to 365 bbls/day (35 to 58 m^3/day)
Maximum Displacement	6,800 tonnes	5,070 tonnes
Arctic Capability Rating	CASPPR Arctic Class IV	CASPPR Arctic Class IV

fragmenting thicker and heavier ice features such as large ridges, large rubble fields and old ice areas into "acceptable sizes" was slower, because repetitive ramming was usually required. The larger icebreakers were generally used for this purpose, when available. It is difficult to highlight time frames for this type of activity since each case was different. However, the following "ball park" numbers will provide some feel.

	one icebreaker	*two icebreakers*
- a large singular first year ridge	tens of minutes	a few minutes
- a thick first year rubble field (several hundred metres in size)	a few hours	an hour or so
- a large rough old ice floe (about 1.5 km in size)	at least half a day	a few hours to half a day
- extreme floebergs or multi-year floes (cold & several km in size)	not breakable	not breakable hard to push

These rough time estimates indicate that two vessels, working together, were more effective in breaking particular ice areas than one, working for twice as long. This was indeed the case, and is an important point to note. For example, during trials with the Terry Fox and Ikaluk in January 1984, the two vessels were spaced about 200m apart and moved through heavily deformed first year pack ice. In addition to the individual tracks they broke, the ice area between them was fragmented by frequent cracks that propagated between the two advancing icebreakers. This particular case involved vessel transit speeds of about 5 knots.

Here, it should also be noted that all of Gulf's icebreakers were constructed to Arctic Class IV standards (now CAC 2). As such, they had the hull (and machinery) strength to operate aggressively in all types of first year ice conditions, without any fear of damage. In old ice, they often had to reduce their ramming and "broken ice" transit speeds, depending upon how "hard" the ice was. However, when operated sensibly, the risk of damage in old ice was not particularly high. In short, all four icebreakers were quite comfortable with aggressive ice management activities, which is an important factor to appreciate.

During stationkeeping operations, the suitability of different ice management techniques that were being used to support the Kulluk was continually evaluated in real time, in terms of:

- their effectiveness in reducing ice load levels on the vessel
- the speed and efficiency with which they were carried out

This Kulluk's real time performance monitoring system, combined with good communication between the Kulluk and support icebreakers, were very important in this regard.

From the experience base that developed, the most effective ice management techniques were documented in the form of recommended ice management guidelines, for both stationkeeping and towing operations. In addition to promoting systematic, well informed and coordinated ice management activities, the basic incentives for the use of these guidelines were:

- to reduce the ice loads on the Kulluk from both "normal" and potentially hazardous ice features and in turn, reduce vessel motions and line tensions, thereby increasing drilling efficiency.

- to enhance the clearance of managed ice pieces around the Kulluk, and allow it to do some icebreaking on its own

- to avoid inappropriate ice management techniques that could result in more severe ice loads on the Kulluk*.

- to reduce the amount of icebreaking being carried out by the support vessels to achieve the required level of ice management and in turn, reduce vessel fuel consumption

- to reduce the ice resistance on the Kulluk while under tow and improve its tow transit efficiency

* One may think the more the ice was broken, the lower the ice loads would be. However, this was not necessarily the case, since load levels were related to the manner in which the managed pack ice interacted with and cleared around the Kulluk, which often depended on how it was managed updrift of and around the vessel.

The more effective ice management strategies and techniques contained in the Kulluk's ice management guidelines are highlighted as follows.

Picket Boat Approach

In situations involving thick, rough first year pack ice, often with old ice floes interspersed throughout it, an ice management technique referred to as "the picket boat approach" was usually used. This technique, or strategy, is illustrated in Figure 5.4.

By way of explanation, the Kulluk's ice monitoring system provided "continuous" information about the pack ice conditions and hazardous features within the updrift sector of actual and expected ice movement. Support icebreakers were deployed in this sector, which was centred along the "ice drift line", at various distances from the Kulluk. Because the majority of the pack ice was thick and present in relatively large floes, it was necessary to break all of the oncoming ice cover into fragments in the order of 50m in size, to keep load levels within acceptable bounds. As noted earlier, the larger icebreaker(s) would normally be positioned furthest up the drift line, to carry out the "heavy" initial icebreaking at a comfortable distance from the Kulluk, in terms of the time of arrival of managed ice. A smaller icebreaker would be positioned at a closer distance, roughly equivalent to the secure time (ST) times the ice drift speed. Its role was to continue to break the moderately sized floe fragments produced by ice management further updrift into smaller pieces, again in the range of 50m in size. In addition, this vessel could directly identify any hazardous ice areas that may have been missed, hence the term "picket boat". Another vessel (if available), was usually positioned for tactical support close-in, within a few hundred metres of the Kulluk, to carry out any final icebreaking or clearance duties that may have been required.

This ice management strategy worked well. Obviously, it was closely tied to the Kulluk's ice alert procedures inasmuch as hazardous features that could not be adequately managed were identified by the support icebreakers in a timely manner. This allowed for a smooth transition through the alert colour code sequence and the response actions that were required, in particular in going from yellow to red.

In terms of updrift ice management, both the "normal" pack ice and any hazardous features within it had to be dealt with. In this regard, the following comments are relevant.

- in "normal heavy" pack ice conditions, vessel transit and breaking speeds were in the range of 6-9 knots on average, including turns. At these "ice management speeds", an updrift sector in the order of 3 x 2 km in extent could be broken into fragments ≈ 100-150m in size, by one icebreaker*, in roughly 3-5 hours. Clearly, two icebreakers working together in this type of heavy ice sector would be more expedient.

- in the sector area closer to the Kulluk, where the picket icebreaker would be working for example, the managed ice "swath width requirement" was generally less than that further updrift, since there was more certainty about how and where the "local ice" would move. "Final management" of the floe fragments in this close-in broken ice zone was a fairly rapid, yet ongoing operation. Typical sector areas needing final fragmentation were in the range of 1 km^2, with related ice management time frames of an hour or so, for one vessel.

- these estimates provide some feel for the time required to manage certain ice areas, in isolation of the ice drift speed. Obviously, ice management demands increased as the drift speed increased, in direct proportions. In this regard, normal ice drift speeds were in the order of 0.3 knots, or about 0.15 m/sec. At this rate, the pack ice would advance about 2 km over a several hour period, and it was not difficult for the icebreakers to "keep up". As drift speeds increased, more ice had to be broken on a unit time basis. For example, at 0.6 m/sec, two icebreakers working the 3 x 2 km sector area example for 3-5 hours could comfortably handle the pack ice "flux".

- the other ice management factor involved hazardous ice features within the normal pack, for example, areas of heavy first year ridging and/or rubble and, at times, thick old floes. These heavy ice areas required "special attention", and usually needed dedicated effort from one or more icebreakers to fragment, taking up variable amounts of their "available time". The primary techniques that were used to manage these heavy ice features are highlighted below, in the form of brief comments. They are intended to provide some feel for the range of methods employed in a generic way, because each case was specific and different.

* 20 to 30 nautical miles of linear transects by one icebreaker through the ice in this type of sector area, plus the natural fractures that normally occurred between successive tracks and floe boundaries, can be used to account for this time estimate.

Repeated Ramming

- ramming was often the only way to penetrate and fragment heavy ice features
- selection of "low relief or apparently weak" areas through which cracks might propagate was a noted consideration
- ramming speed limits were also a factor in cold (or hard) old ice

Breaking "Behind"

- breaking the "normal ice" behind (and around) heavy features was a noted option, before starting to deal with them
- this "loosening" tended to enhance the likelihood of fractures propagating through the heavy ice features, and sometimes provided "room" for heavy ice fragments to move apart, making subsequent rams easier

Slow Thrust

- for warm thick rough first or second year ice features, "notching the icebreaker in" and applying constant thrust "slowly" was often more effective than ramming, to propagate major cracks (Figure 5.5)
- after a few minutes of this type of thrust application, large cracks through the feature tended to open up quite rapidly, and the vessel could push its way through

Pushing Features

- large rough features that were difficult (or impossible) to fragment in a timely way were sometimes pushed off the ice drift line (Figure 5.6)
- two or more icebreakers working in sensible positions were required to keep ice feature rotations in hand

- the availability of tens of thousands of horsepower made this pushing approach quite effective, particularly in fairly loose pack ice conditions

As pack ice concentrations decreased, the picket boat concept was still used, and heavy ice areas dealt with by the range of techniques cited above. Clearly, ice management demands were lower, and activities more comfortable, in most of these lower concentration situations.

"High Speed" Approach

In situations that involved high concentrations of fairly thin first year ice, without significant amounts of old ice, a "high speed" ice management technique was usually used, often with two icebreakers working in tandem. This technique is illustrated in Figure 5.7. The intent of the approach was to fragment large "swaths" of pack ice updrift of the Kulluk in a quick and efficient manner. The rationale for this technique is outlined as follows, together with a few related comments:

- when the Kulluk's support icebreakers transitted fairly thin ice at high speeds, their bow and wake waves would propagate outwards, over distances of several hundred metres on each side of the vessel. This would induce flexural failures in the thin pack ice, creating a wide swath of small ice "platelets", from a few metres to a few tens of metres in size.

- this type of high speed icebreaking activity could rapidly deal with most (if not all) of the oncoming pack ice in the "updrift sector", including small ridges, with a limited number of periodic runs. In this regard, two vessels moving up and then back along the drift line in tandem, at 10 knots, could break a swath about 5 km in length and 1 km in width, in roughly 30 minutes. The icebreaking vessels could then standby the Kulluk for any tactical support that may be required, without consuming much fuel.

- from the Kulluk's perspective, these thin ice platelets resulted in low load levels and as importantly, tended to "flow" around the vessel and clear well, unless the pack ice cover was very tight or under pressure.

- it goes without saying that there were many variations to this ice management approach.

- sometimes, only one icebreaker was dispatched to create a broken swath updrift of the Kulluk, which usually took a little more than twice the time of tandem runs, to accomplish the same end
- sometimes, a vessel would have to be dedicated to breaking heavy features within the oncoming thin pack ice cover, using the types of techniques described earlier
- in tight pack ice conditions, this high speed ice management technique was still preferred, but a dedicated vessel was usually positioned close-in, to help clear ice around the Kulluk on an as-required basis

Prior to developing this technique during the Kulluk's "first late season operation" in 1983, an ice management approach that Canmar had used to support their drillships in thin first year ice was employed (see Figure 5.8). This technique, which involved a "continuously circular" updrift icebreaking scheme, was applied defacto, because most of Gulf's icebreaker Masters had previously worked for Canmar. The approach generally worked inasmuch as it usually kept load levels within acceptable bounds. It did however, have the following downsides.

- the pack ice was usually overmanaged as a consequence of this approach, since it was continually worked, which created very small ice pieces and rubble. This may have been required to "protect" the exposed mooring lines on Canmar's drillships, but in the case of the Kulluk, typically resulted in:

    - thicker ice rubble in the managed ice area, because of refreezing
    - poorer ice clearance around the Kulluk and in turn, higher load levels

- a continuous and unwarranted "milling about" of the support icebreakers as they carried out this type of ice management activity, with higher levels of fuel consumption

Ice Clearance

In tight managed ice and pressure situations, the techniques used to clear any ice fragments or rubble that had accumulated on the updrift face of the Kulluk were important, in terms of reducing load levels. In this regard, the following lessons should be noted.

- a direct icebreaker approach to 'push off' rubble wedges or blocked floe fragments on the Kulluk's updrift side was inappropriate, since icebreaker impact forces were usually transferred directly to its mooring system. Additionally, the icebreaker sometimes faced the possibility of being trapped between the oncoming ice and the Kulluk.
- reasonably directed icebreaker prop wash, together with "back and forth" movements close to the Kulluk's port and starboard quarters, were considerably more effective in terms of clearing rubble and tight ice, thereby reducing load levels (Figure 5.9)
- close icebreaker passes of a circular nature, within tens of metres of the Kulluk, were also quite effective in this regard, at least to temporarily relieve loads on the vessel

Stationary Ice Situations

Stationary ice conditions were infrequent, but when they occurred were not easy, since the "next sector" from which the pack ice would move was not known. In this case, the best ice management strategy was to fragment the ice cover within a 1-2 km radius of the Kulluk into reasonably sized pieces, then simply standby until the ice started to move again.

Ice Pressure Situations

Ice pressure situations were also infrequent. However, when they occurred, these situations presented real challenges for the Kulluk and its ice management system. In light ice pressure, techniques involving icebreaker prop wash, back and forth movements along the sides of the Kulluk, or continually circling it, were useful. As the level of ice pressure increased, circling manoeuvers by the icebreakers became more difficult, since they had difficulty turning. Any ice management on the updrift side of the Kulluk was also problematic, because it encouraged rafting and ridging, which created significantly thicker ice rubble and amplified load levels.

The best strategy in significant ice pressure situations was not to overmanage the ice, but simply try to enhance its clearance in close proximity to the Kulluk. In this regard, icebreaker support activities were very limited during pressure events. The approach that was usually preferred in heavy pressure situations is illustrated in Figure 5.10. Sometimes, this ice clearance scheme kept load levels within acceptable bounds until the pressure event subsided. However, in a few cases, load levels kept increasing and the Kulluk was forced to move-off.

Communication, Coordination & Responsibilities

Good communication between the support icebreakers and the Kulluk was an essential part of ice management operations. Obviously, information about ice conditions and movements, ice management priorities and strategies, and the effectiveness of the work being carried out by each icebreaker had to be continually exchanged. When the Kulluk first encountered ice, and ice management activities commenced, these information exchanges were more “off the cuff” than systematic. The icebreakers tended to communicate well amongst themselves, but relevant information transfer from the Kulluk, or to it, sometimes “fell between the cracks’. With time, lines of communication, procedures to coordinate ice management activities, and related responsibilities became better defined. The approach that was adopted involved the following key elements.

- overall control of ice management actvities was from the Kulluk’s control room (bridge), including requests to send additional icebreakers to site, as required

- the Marine Superintendent (whose role was similar to a “Kulluk captain”, yet reported to the Kulluk’s OIM) was responsible, accountable, and had the final decision making authority for:

  - developing and communicating ice management strategies and priorities to the support icebreaker in a timely manner
  - communicating with and obtaining feedback from the icebreakers regarding the progress and effectiveness of their ice management activities, and any hazardous ice conditions or situations they felt may be arising
  - assessing this ice management information as a key input to the ice alert system

- the icebreaker Masters, who implemented and carried the ice management strategies out, were responsible, accountable, and had the final authority for:

  - the operation of their vessel in conducting their ice management tasks
  - the specific way in which they carried out these tasks, on a tactical basis
  - communication with the Kulluk, including recommendations and concerns
  - communicating with and coordinating their ice management activities with the other icebreakers supporting the Kulluk- usually, the most senior Master took a lead role in this regard

- the Ice Advisor, who worked onboard the Kulluk as the Marine Superindent's "right hand man" on ice, Kulluk performance and ice management issues, was responsible for:

  - providing information, assessments and recommendations about ice conditions, hazards, ice management strategies, Kulluk performance, alert levels and so forth
  - in many cases, functionally carrying out most of the Marine Superintendent's ice management duties

An example of the type of ice management strategy that was routinely developed onboard the Kulluk, and sent to the icebreakers, is shown in Figure 5.11. The manner in which information about pack ice conditions and their degree of severity, expressed in relation to the alert codes they could evoke, is evident. These types of maps, which were updated on an as-required basis, focused the exchange of relevant information between the Kulluk and icebreakers, and helped ensure that "everyone was working on the same page". Here, it should also be noted that the Masters and Mates who operated the icebreaking support vessels benefited from a good understanding of how the "entire Kulluk system worked together". To meet this need, ongoing education and training was an important factor.

Although the ice management systems outlined in this section of the report are specific to the Kulluk's operations, it should be clear that some of the underlying philosophies and methods used are relevant for floating systems in other ice infested areas, such as the Grand Banks.

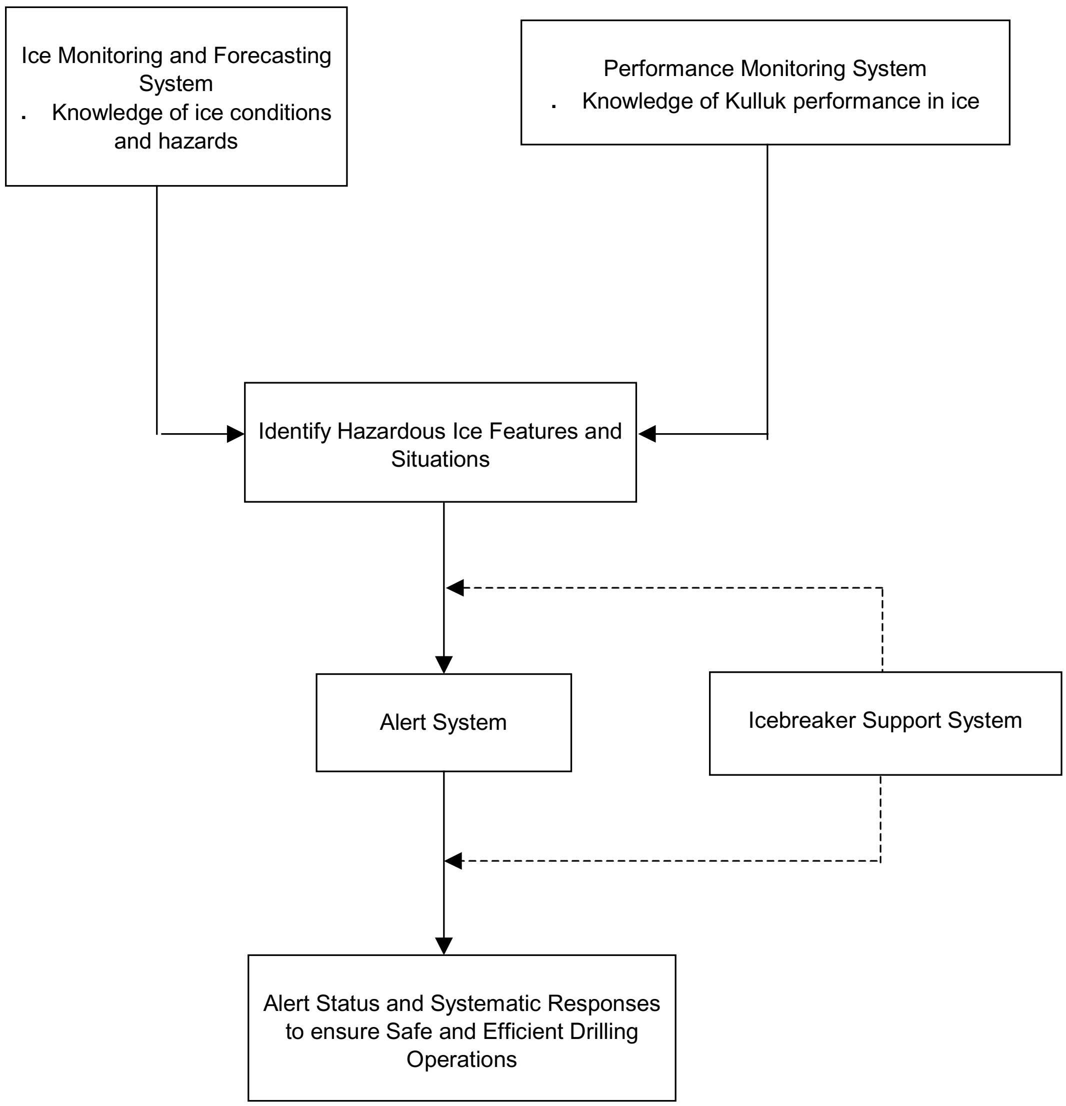


Figure 5.1: The basic components of the Kulluk's ice management system are shown here, along with the manner in which they were used together. The logic for this approach is quite straightforward.

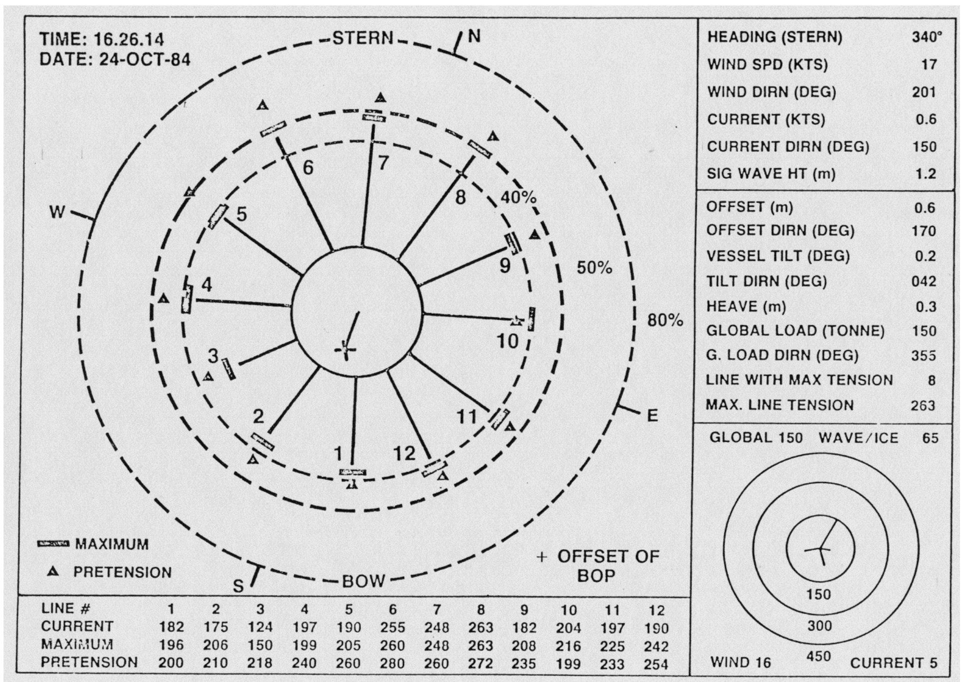


Figure 5.2: An example of the real time information display that was used in the Kulluk's control room. This system provided information about Kulluk anchor line tensions, global load levels, offsets and other pertinent factors on a continuous basis. It was extremely useful in terms of integrating information from a variety of sources and displaying it in a simple, understandable and visual manner.

KULLUK ENVIRONMENTAL ALERT STATUS

COLOUR CODE	MEANING	HAZARD TIME (HT) MINUS SECURE TIME (ST)	DRILLING RESPONSE	MARINE RESPONSE
Green	Normal operation	HT-ST is more than 12 hours	Normal operations	Normal watch
Blue	Early alert	HT-ST is less than 12 hours	Normal operations	Alert watch & ice management
Yellow	Early warning	HT-ST is less than 6 hours	Restrict operations to available lead time	Begin preparations for hazard and ice management
Red	Drilling must stop, vessel may move off	HT-ST is zero	Secure well as appropriate	Final preparations for hazard and ice management
Black	ICE: vessel must move off WEATHER/WAVE: vessel must stream off on moorings	HT for disconnect is less than 2 hours	Disconnect	ICE: Move Kulluk off site WEATHER/WAVE: Stream off on moorings

Figure 5.3: This figure provides a synopsis of the Kulluk's ice alert system. Colour codes, their meaning, relevant time frames, and the type of drilling and marine responses that were associated with them are all indicated.

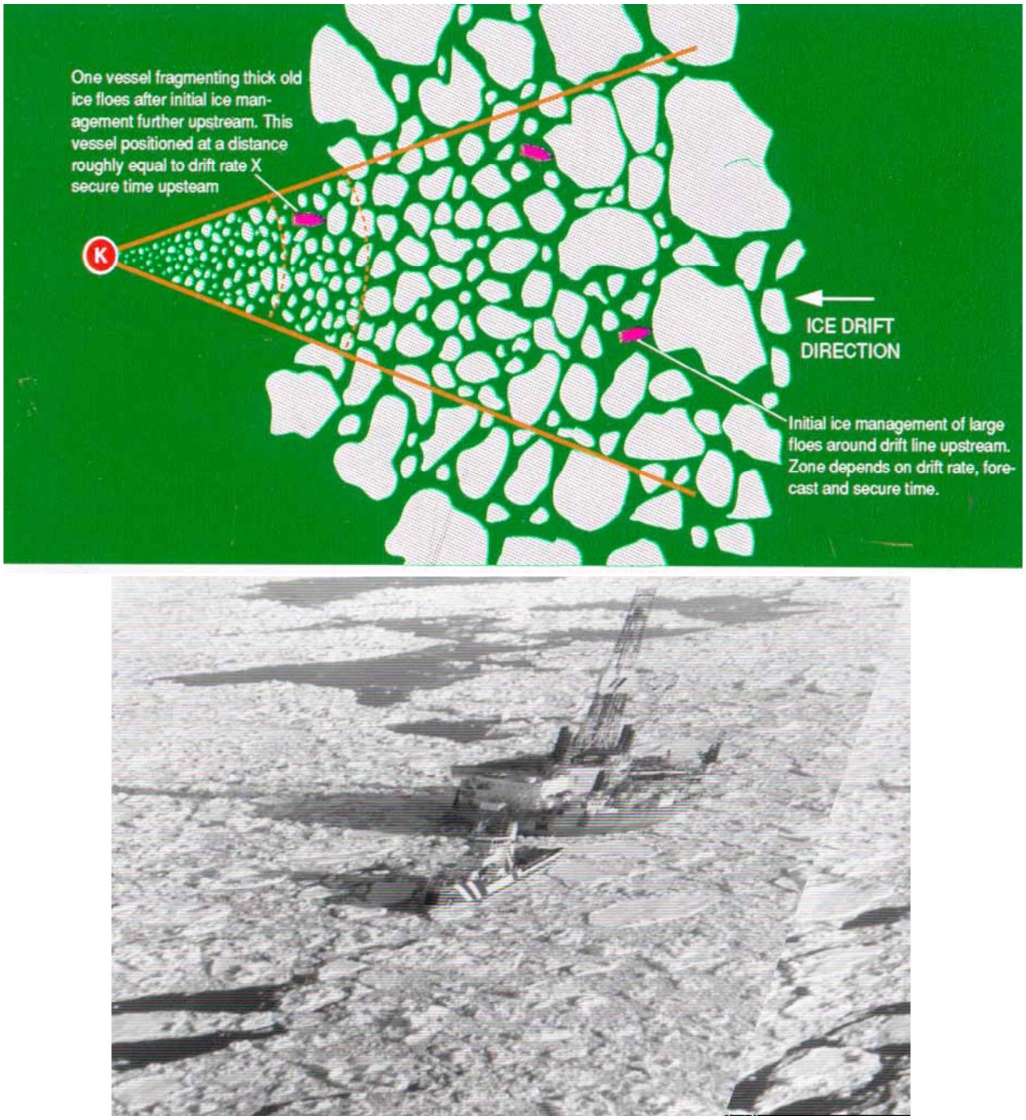


Figure 5.4: The picket boat ice management strategy is schematically illustrated in the upper part of this figure. This approach was usually used in heavy pack ice conditions and was very effective. The lower photo is representative of the type of managed ice conditions that it would generally produce around the Kulluk.

Figure 5.5: In thick rough first or second year ice features that were relatively warm "notching in the icebreaker" and applying a constant thrust "slowly" often propagated major cracks, which would split the feature apart.

Figure 5.6: Large rough ice features that were difficult to fragment in a timely way were sometimes pushed off the ice drift line. Obviously, the lower the pack ice concentrations were, the easier it was to push floes.

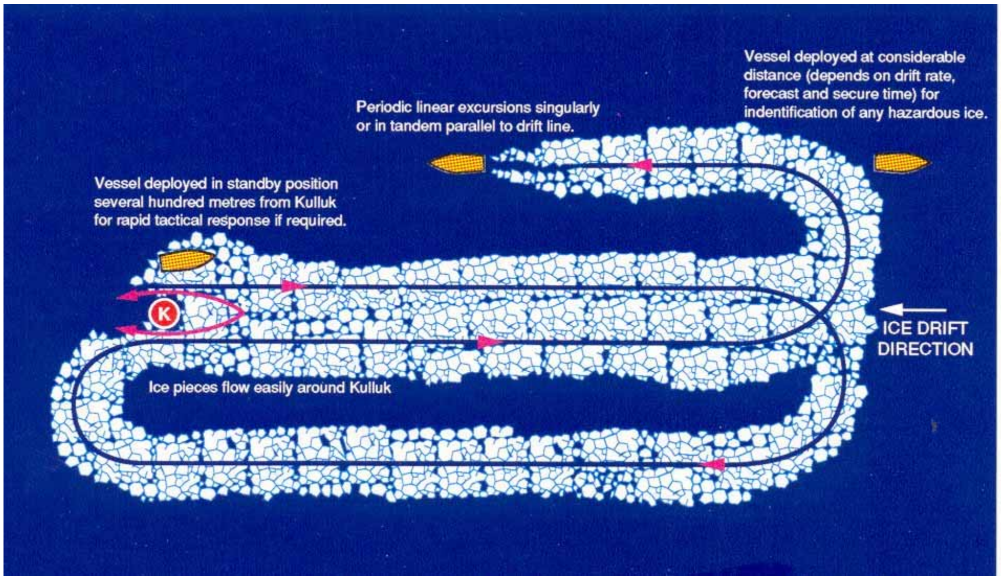


Figure 5.7: An ice management technique that involved high speed icebreaker transits, often in tandem, was used to quickly fragment large "swaths" of pack ice, particularly in fairly thin first year ice conditions. This method is illustrated in the upper part of the figure. After running "up and then back" along the drift line, the icebreakers would stand by the Kulluk for any tactical support that may have been required, thereby saving fuel (lower figure).

Figure 5.8: This photo shows a circular ice management technique that Canmar normally used to support their drillships, in very thin pack ice conditions. Support icebreakers continually circled updrift, breaking the ice into extremely small pieces (a metre or less in size). However, this method often produced ice rubble that was considerably thicker than the original unmanaged ice. It would freeze and could become quite formidable in low temperatures.

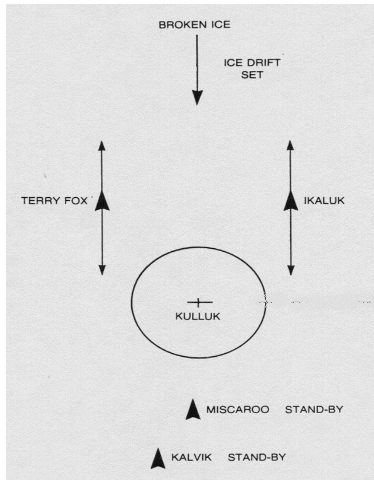


Figure 5.9: Directed prop wash, and "back and forth" movements of icebreakers in close proximity to the Kulluk like those illustrated here, were quite effective in reducing load levels in tight managed pack ice conditions. Enhancing ice clearance was particularly important in this regard.

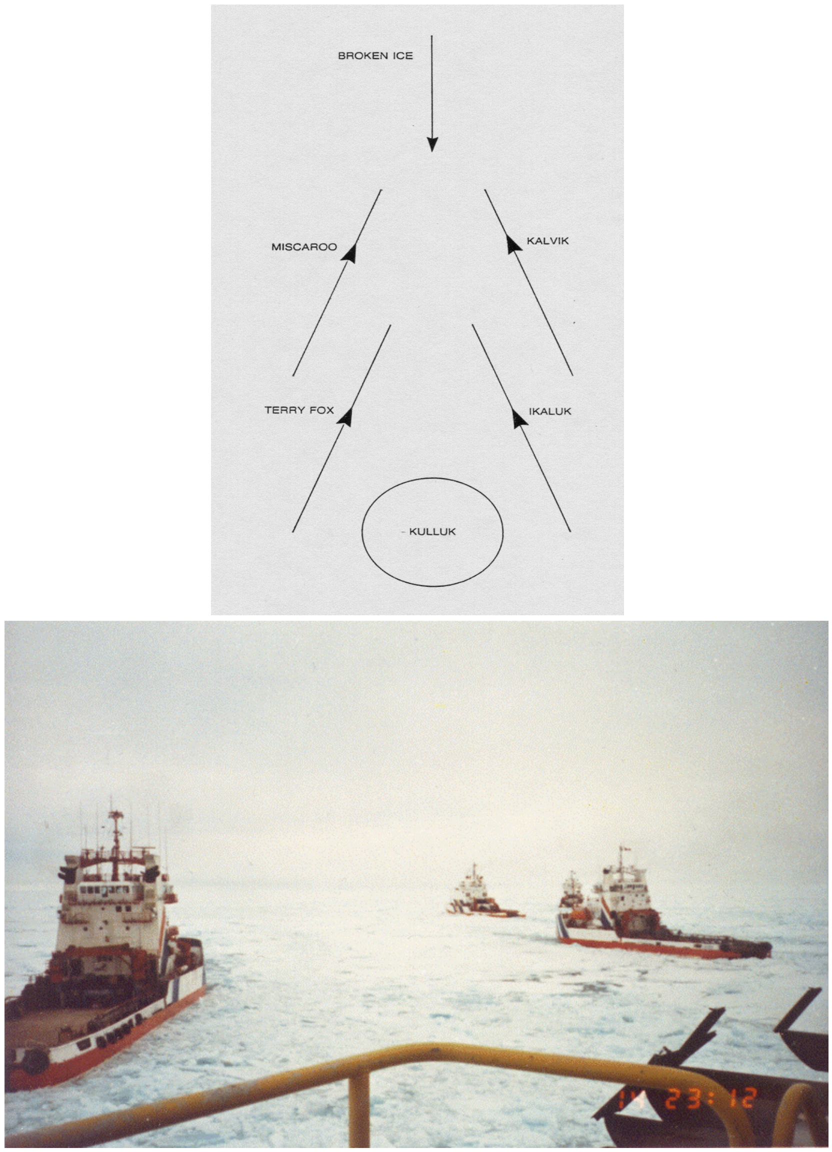


Figure 5.10: In heavy ice pressure, minimizing the amount of icebreaking that was carried out around the Kulluk was important, to "keep load levels down". Close-in ice clearance support, such as the method illustrated in the upper part of this figure, was sometimes effective in keeping loads within acceptable bounds. The lower photo shows this technique being applied in a pressure situation.

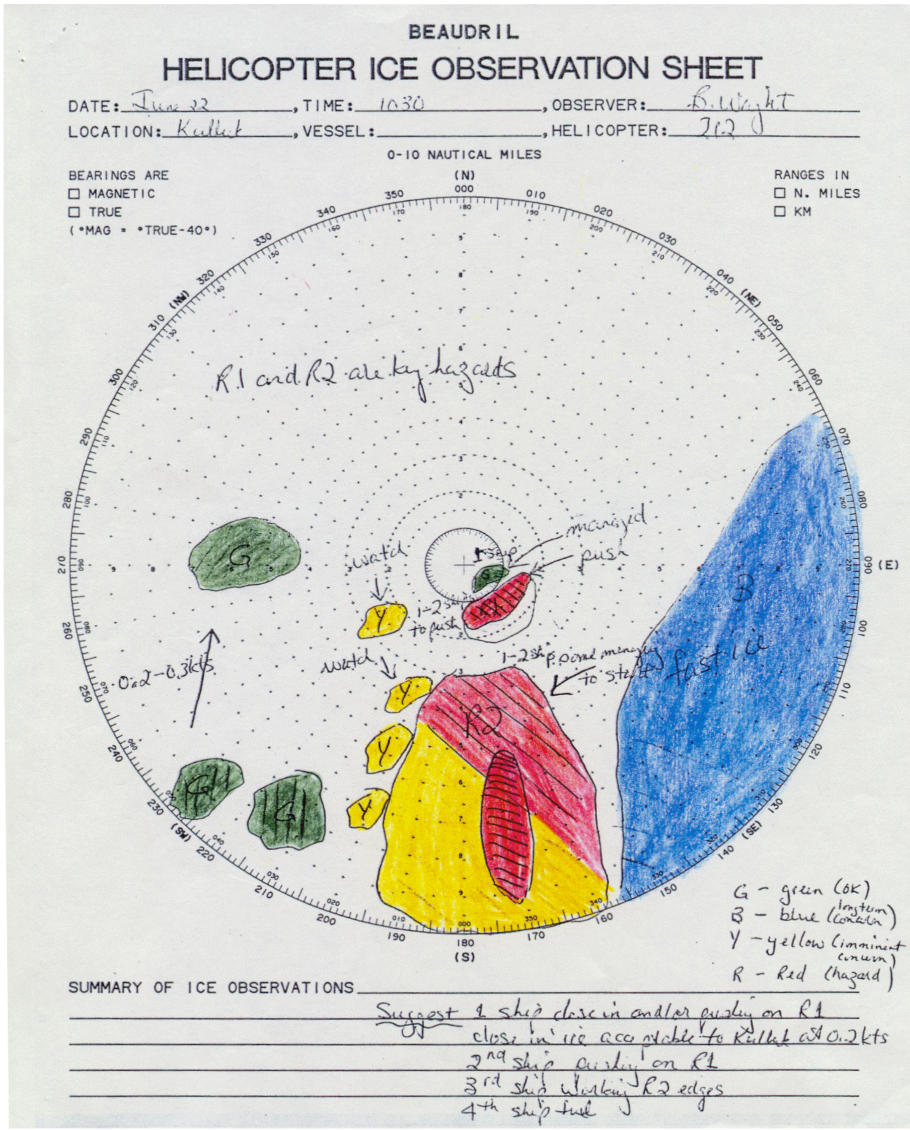


Figure 5.11: An example of the type of "living" map product that was routinely used to communicate ice management stratagies, and to send relevant information back and forth between the Kulluk and its support icebreakers. This type of near real time information helped ensure that everyone was "working on the same page".

6.0 Ice Management Assessment

6.1 General

In the preceding section of this report, the ice management systems that were used to support Kulluk stationkeeping operations have been highlighted, along with the key ice management methods employed. These ice management activities were designed, and then tuned, to reduce load levels on the Kulluk in moving pack ice conditions, and to mitigate risk. Here, some of the more operational aspects of the Kulluk data are presented and discussed, with the intent of illustrating salient features of the information, relative to questions regarding ice management and risk.

To summarize relevant Kulluk information and some of its key implications, a number of logical "areas of interest" were first identified. The Kulluk data base was then evaluated in the context of these areas of interest, as outlined below. Although the results shown are "Kulluk specific", the perspectives they provide can be applied more generically, for other types of floating system operations in managed ice.

6.2 Influence of Icebreaker Support

6.2.1 Number of Vessels

The most basic question that is usually asked about ice management involves the number of icebreaking support vessels that may be required. This question is not straightforward, since the correct answer is related to a range of factors. They include:

- the pack ice conditions that are expected
- the "resistance" capabilities of the moored vessel
- the performance capabilities of the support icebreakers

- the amount of downtime that is considered acceptable
- the ability of, and time frames for, the moored vessel to move-off location

In the case of Kulluk stationkeeping operations, up to four highly capable icebreakers could normally be called upon, within a day or two notice, to carry out various ice management support activities, on an as-required basis. Figure 6.1 shows the number of icebreakers that were used to support Kulluk operations during the events contained in the Kulluk data base, in different pack ice regimes. This scatter plot excludes events involving ice pressure. To better display the information, the individual data points have been spread both horizontally and vertically, by adding a random value (between ± 0.5) to their integer values. The following points should be noted.

- between one and three icebreakers were generally used to support Kulluk operations, across all types of pack ice regimes. The fact that several icebreakers were often used in relatively easy pack ice conditions, while only one or two vessels were sometimes used in heavier ice, is related to a number of practical factors, which include:

  - changes in pack ice conditions that could occur over fairly short time frames
  - the availability of icebreakers to send to the Kulluk at any point in time
  - commercial incentives to employ and "charge-out" the icebreakers

- notwithstanding this point, Figure 6.1 indicates a discernable trend towards an increased number of support icebreakers with increasing pack ice severity, as one would expect

- the cluster of data points that shows four icebreaking support vessels in fairly light ice conditions (pack ice regimes 2 & 3) is associated with Kulluk operations after Canmar had purchased the vessel in 1993. It is quite likely that these "outlying points" were driven more by commercial considerations, than by real ice management needs

6.2.2 Effect on Loads

The next question that is usually asked relates to the influence of ice management in reducing load levels on moored vessels in pack ice. Again, this question is multi-facetted. As rough "rules of thumb", the following points are first noted, on the basis of the Kulluk load data.

- well managed level ice should result in peak ice load levels that are about 20% of those in unmanaged level ice, providing it clears well around the vessel (see Table 6.1)
- in tight managed level ice conditions that do not clear around a vessel well, load levels will still be about half (or less) of those expected in unmanaged level ice

- unbroken ice features like large first year ridges and sizable thick ice floes (eg: old ice) have the potential to cause very high load levels, quite rapidly

In Figure 6.2, measured loads are summarized relative to the number of support icebreakers used, for all of the events in the Kulluk data base, in pack ice regimes 9 and 10. Accordingly, this plot reflects the range of loads experienced in managed ice, in 9 - 10/10ths medium and thick first year pack ice conditions, with ridges, rubble and occasional old floes. Again, events involving ice pressure are not included in this figure. The following points should be noted.

- two or three icebreakers were almost always used in these types of high concentration, heavy pack ice situations. There are only a handful of cases where one support vessel was employed, and only two cases with four icebreakers.

- there is a high degree of scatter in the range of loads that were seen, regardless of the number of support icebreakers used. Clear trends are not immediately obvious. However, this should not be particularly surprising, given the wide variety of individual situations, with different specifics, contained in the plot.

- on closer examination, the data does tend to suggest a higher level of reliability in keeping load levels down, as the number of vessels increases. This is an important observation.

Figure 6.3 provides a clearer illustration of this trend. To generate this plot, load values at the 0.95, 0.8 and 0.5 percentile levels were first calculated for the data groups involving different numbers of support vessels. Best fit curves (exponential in this case) were then fit through these values. As shown in Figure 6.3, there is a strong trend towards lower load levels in the less frequent, yet "harder to handle" ice events, as the number of icebreakers increases. This is a practical result, which makes good sense.

Figures 6.4 and 6.5 present similar load summaries for all of the events involving ice pressure. It is interesting to note that the general load trends for these events are opposite to those for unpressured ice. These figures tend to support some of the comments made earlier, namely, that overly managed ice in pressure situations usually gives rise to higher load levels. Kulluk load data summaries for all of the events in the remaining pack ice regimes are given in Figures 6.6 and 6.7, again in relation to the number of support icebreakers used. In these figures, the trend toward lower load levels with increasing numbers of vessels is more visually apparent. These plots also tend to reinforce the rather obvious comment that more support icebreakers generally result in lower “maximum load levels” in a particular pack ice regime, with a higher degree of reliability. However, it is important to recognize that load levels in these “lesser ice regimes” are typically low, even for situations involving ice management with one or two icebreakers.

6.2.3 Effect of Drift Speed

Another question that is often asked relates to the influence of increasing ice drift speed on the effectiveness of ice management support, and in turn, on ice load levels. As noted earlier, the combination of high drift speeds and heavy pack ice situations were often challenging for Kulluk operation, from an ice management standpoint, since more ice had to be dealt with on a unit time basis. However, the support icebreakers were usually capable of “keeping up”, and load levels were generally kept within acceptable bounds.

In the original full scale data evaluation report (Wright et al, 1999), it was shown that load levels were not particularly sensitive to drift speed, in managed ice conditions, across a broad range of thicknesses. Here, further attempts were made to identify trends between load levels and drift speed for different pack ice regimes, in relation to the number of support icebreakers used. These attempts were largely unsuccessful. In this regard, the most practical comment to make is that the ice management system normally kept up with the oncoming pack ice and its interactions, across the range of drift speeds and ice conditions encountered.

Figure 6.8 provides a simple summary of the number of support icebreakers used in various pack ice conditions, as a function of ice drift speed, for all events in the Kulluk data base except those with pressure. For the purposes of this summary, the pack ice regimes in which operations were being carried out have been combined into the following broad groupings.

- regimes 7, 8 9 and 10, to represent close to very close "heavy" pack ice situations
- regimes 2,3, 5 and 6, to represent very open to open concentrations of "heavy" pack
- regime 4, to represent high concentration yet thin first year pack ice conditions

A few generalized comments can be made on the basis of the information in this figure, which are outlined as follows.

- in close to very close pack situations (7 - 9+/10ths) involving heavy ice (medium and thick first year ice types with ridging, rubble and occasional old ice floes), two to three support icebreakers were usually used for ice management, in ice drift speeds to 0.85 m/sec (1.7 knots). The scatter plot for this data grouping (top plot in Figure 6.8) suggests a slight trend towards a more frequent use of three vessels as drift speeds increase.

- in very open to open pack situations (1 - 6/10ths), again involving heavy ice, one to two icebreakers were more commonly used than three (middle plot). Ice drift speeds of up to 0.75 m/sec (1.5 knots) were accommodated by this level of ice management support. The data points that indicate the use of four vessels in low to moderate drift speed ranges are viewed as "outliers", and not representative. (in these cases, from 1993, Canmar had four support vessels on site, typically in 1 - 3/10ths ice concentrations, which was overkill. It is noted, however, that ice loads were kept to almost zero levels).

- in high concentrations of thin first year pack ice (lower plot) two and, most often, one support icebreaker was sufficient to adequately manage the oncoming ice cover, in drift speeds to 0.75 m/sec (1.5 knots).

- as a concluding and very pragmatic comment, the information in Figure 6.8 also tends to say that ice management operations around the Kulluk "generally made do", with the icebreaking resources that were available at the time.

6.3 Perspectives on Risk

The Kulluk data can also be used to obtain some perspectives about levels of risk, or at least perceived levels of risk, for moored vessel operations in various pack ice conditions, with ice management support. The foregoing discussion has provided some feel for the influence of icebreaker support, in relation to the number of vessels used in different ice situations, and their effect in terms of maintaining load levels within certain bounds. Here, the alert status information for events in the Kulluk data base is highlighted in relation to several key factors, as a indicator of risk.

6.3.1 Influence of Pack Ice Severity

The Kulluk's ice alert system, as described in Section 5.4, contains a sequence of alert colour codes that progressively reflect how close a "hazardous ice situation is becoming", in terms of its time of arrival. These alert colour codes move from green, to blue, to yellow, to red and then to black (a move-off), and provide a measure of increasing levels of risk.

The first and most obvious question to ask relates to the degree of risk that a moored vessel operation faces in different pack ice conditions. For the Kulluk, or any other system using icebreaker support to manage the ice and thereby reduce ice load levels, this is an integrated question. Clearly, it involves the performance capabilities of both the moored vessel and the icebreaker support system. Figure 6.9 shows a scatter plot of the Kulluk's alert status during each event in the combined data base (ie: the original and new data entries), as a function of the pack ice regime in which operations were being carried out. This figure, which excludes events involving ice pressure, gives a feel for the risk levels experienced by the Kulluk in a broad range of pack ice situations. Again, the individual data points have been "spread out", to better display the information. Here, the following points should be noted.

- the proportion of yellow and red alerts in the data, which can be viewed as representing moderate and high risk situations, respectively, increases as the severity of the pack ice conditions increases. This is by no means surprising and is what one would expect.

- most of the red alerts are clustered in 9 - 9+/10ths heavy pack ice conditions (ice regime 10). However, the number of red alert events is low in relation to the total number of event data points in this category.

- some red alerts were called during operations in the lesser pack ice regime categories (2, 3, 5 and 6), because of large, thick, rough ice floes moving to within close proximity of the Kulluk as they were being managed. None of these red alerts progressed to a black alert and a move-off location. However, a few hours of time was lost during each of these events, since drilling operations were suspended, in case a move-off was actually required.
- no red alerts were called in thin first year pack ice (regime 4), without ice pressure (one red alert did occur in a heavy pressure situation in 1983, when the ice was overmanaged).

6.3.2 Risk & Load Levels

It is also of interest to consider the alert status, or level of risk, under which the Kulluk was operating when certain ice load levels were experienced. This information is summarized in Figures 6.10 and 6.11, for all of the events in the Kulluk data base. Figure 6.10 shows a scatter plot of the alert status in-place during each event versus the measured load, for cases not involving ice pressure. Figure 6.11 provides a similar plot for situations when ice pressure was encountered. Again, the data points have been spread out in the y-direction, to better display them. With reference to these figures, the following points are noted.

- there is a clear trend toward increased alert levels with increasing ice loads in both figures. This result should be expected, at least in a general sense, since "preparedness" to shut down operations and move-off should progress through a logical sequence as load levels rise. In this regard, the data indicates the Kulluk's ice alert system worked well and was properly focused.

- within the red alert category in Figure 6.10, there is a cluster of data points at low load levels (< 100 tonnes) and another set of points at higher load levels (> 200 tonnes). The lower load points were associated with the threat of "big heavy ice floes" that either "missed" the Kulluk, or were ultimately managed before impacting it. The higher load points were the direct result of staying on location in heavy managed pack ice conditions.

- two load data points that were not shown in earlier figures have been included in Figure

6.10. These are the two highest red points, which occurred due to "errors in judgement" made onboard the Kulluk during its first month of operations in the Beaufort. The largest event involved one of the "front-end loads" from an indentation into a massive unbroken old ice floe moving at 0.6 m/sec (1.2 knots). This event quickly pushed the Kulluk off, breaking some of its mooring lines in the process. Fortunately, in terms of alert status, the well had been secured and the riser disconnected.

- the load and alert data for ice pressure situations (Figure 6.11) shows that operations in some light to moderate pressure cases was not considered particularly "risky", with good ice clearance support. However, increasing levels of pressure, as indicated by measured mooring loads, or heavy pressure events led to a red alert status and in several cases, a subsequent black alert (ie: a move-off location).

6.3.3 Other Factors

There are a variety of other factors that influenced the ice alert levels called on the Kulluk, and on related perceptions of risk. These factors are briefly highlighted as follows, along with a few relevant comments.

Visibility

Poor visibility conditions, including darkness, had a strong influence on levels of comfort surrounding ice detection, monitoring and ice management. In this regard, poor visibilty was noted as an impediment to icebreaking activities in Section 5, since the support vessels tended to slow down, and become more uncertain about "their degree of ice management success". This was reflected by reduced hazard times (HT) within the Kulluk's alert system and often, an increased alert status. Poor visibility is a factor that is not included in the Kulluk load data base, but is a practical constraint on operations that should not be overlooked.

Drift Speed

As ice drift speeds increased within a particular pack ice regime, there was a tendency for Kulluk alert levels to rise, suggesting higher risk levels. In many ways, this should be obvious, since the hazard times calculated and used in the alert system were directly proportional to drift speed. However, hazards that were of concern from the perspective of both potential ice load levels and, the effectiveness with which they could be managed, had to be present to start off with. The worst situation was often heavy pack ice, moving at high drift speeds, in poor visibility conditions. The events in the Kulluk data base tend to support these comments, but not strongly. Figure 6.12 provides one example. Here, alert levels are shown (by data point colour) in a scatter plot of drift speed versus concentration, for loading events in thick heavy first year pack ice conditions, and in thin first year pack ice, respectively. Both plots involve situations where two support icebreakers were used to manage the oncoming ice cover. In the heavier ice case, red alerts begin to creep into the scatter plot in the 0.3 to 0.4 m/sec speed range (0.6 to 0.8 knots), which is relatively rapid level of ice movement, at least for the Beaufort Sea. In thinner first year ice, which more akin to the Grand Banks in terms of thickness, no red alerts occurred, in ice drift speeds to 0.75 m/sec (1.5 knots).

Number of Support Icebreakers

The number of icebreakers that were available to manage pack ice around the Kulluk had an obvious impact on levels of comfort with the operation, and on the ice-related risks that were perceived. In this work, attempts were made to identify trends between increased ice alert levels and decreases in the number of support vessels used, on the basis of the load event data. However, these attempts met with little success and tended to support the practical point made earlier, namely, that ice management normally "kept up" with the oncoming pack ice, with the icebreaker resources available at the time. Notwithstanding this comment, more icebreakers gave rise to more comfort with Kulluk operations in any given ice situation.

It is also interesting to note a few of the other "icebreaker factors" that played a role. These included:

- the Masters who were onboard and in charge of each support icebreaker, since some "did better work" than others

- the experience of the senior Master who would normally take charge in terms of coordinating specific ice management activities with all the support icebreakers

- any problems the icebreaking vessels may be having at a given point in time (eg: engines being shut down, steerage problems, etc

Obviously, ice management support for the Kulluk was a practical operation, with all of the "ins and outs" that are involved.

In this section, some of the more operationally oriented information in the Kulluk data base has been reviewed, to illustrate its salient features, relative to various questions regarding ice management and risk. Clearly, the information that has been provided is specific to the Kulluk and its icebreaker support system. However, the load data presented, and many of the lessons learned, can be applied more generically, for floating system operations in other ice infested areas. Some of the key implications of this Kulluk information are briefly highlighted next, for Grand Banks development systems.

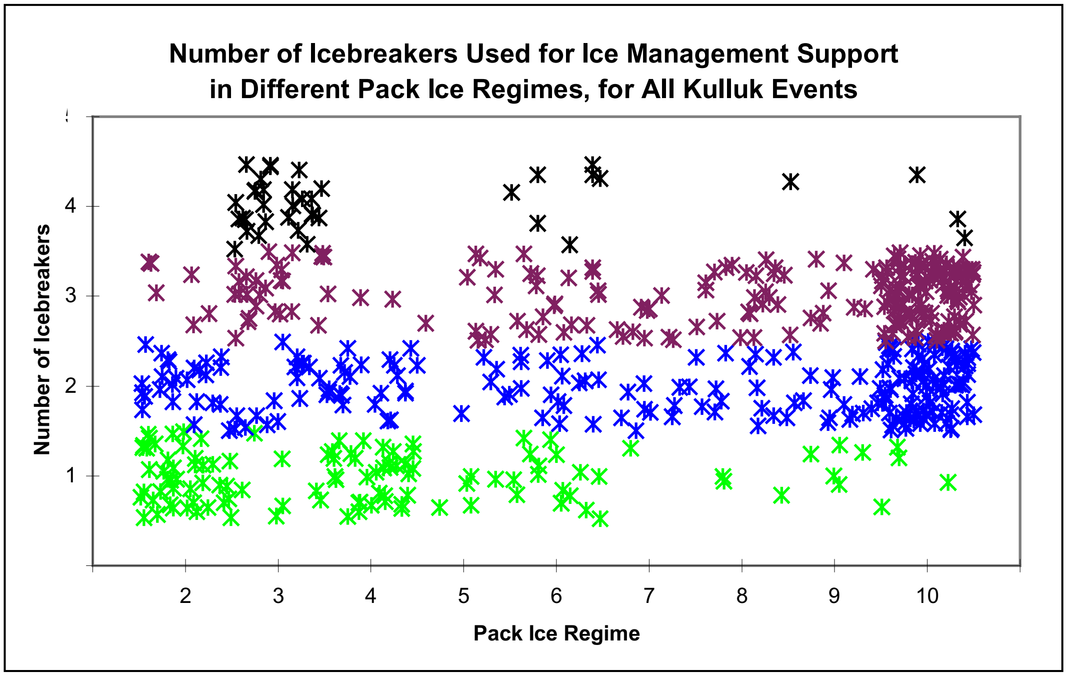


Figure 6.1: Here, the number of icebreakers that were used to provide ice management support for the Kulluk are shown as a function of the pack ice regime in which the vessel was operating. This scatter plot reflects "operational information" that is associated with all of the loading events in the combined Kulluk data base (ie: the original and new event data), excluding those involving ice pressure. Again, pack ice regimes 9 and 10 represent medium to thick first year ice situations, often with some old ice inclusions, with concentrations of 9 - 9+/10ths. Ice regimes 7 & 8, 5 & 6, and 2 & 3 refer to similar medium to thick pack ice conditions, with mean concentrations of 8/10ths, 5/10ths and 2/10ths, respectively. Ice regime 4 covers new to thin first year pack ice conditions, which almost always involved 9 - 9+/10ths ice coverage.

Loads on the Kulluk			
Ice Thickness	**Situation**		
	Unbroken Ice	***Managed Ice with Good Clearance***	***Managed Ice with Poor Clearance***
0.5 m	139 tonnes	50 tonnes	134 tonnes
1.0 m	241 tonnes	69 tonnes	178 tonnes
1.5 m	343 tonnes	88 tonnes	221 tonnes
2.0 m	445 tonnes	107 tonnes	265 tonnes

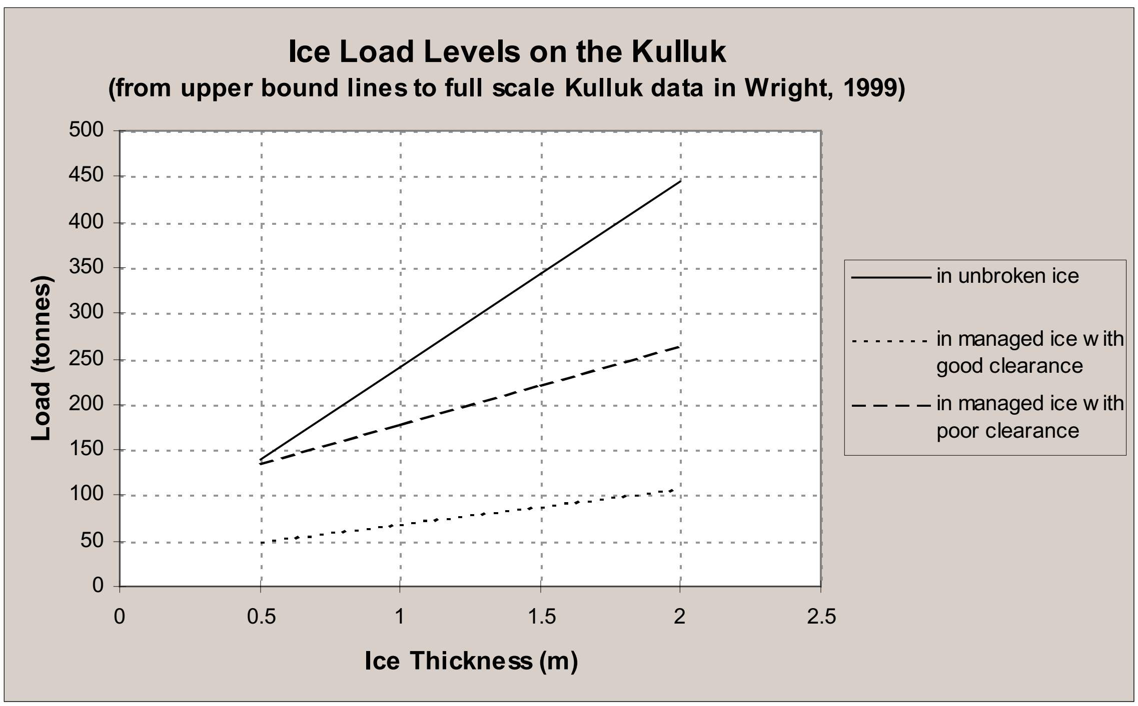


Table 6.1: Load reductions resulting from ice management activities around the Kulluk were substantial. This table highlights peak load levels on the Kulluk in unbroken ice and managed ice, with good and poor clearance. The lower part of this table shows the Kulluk ice load information in graphical form.

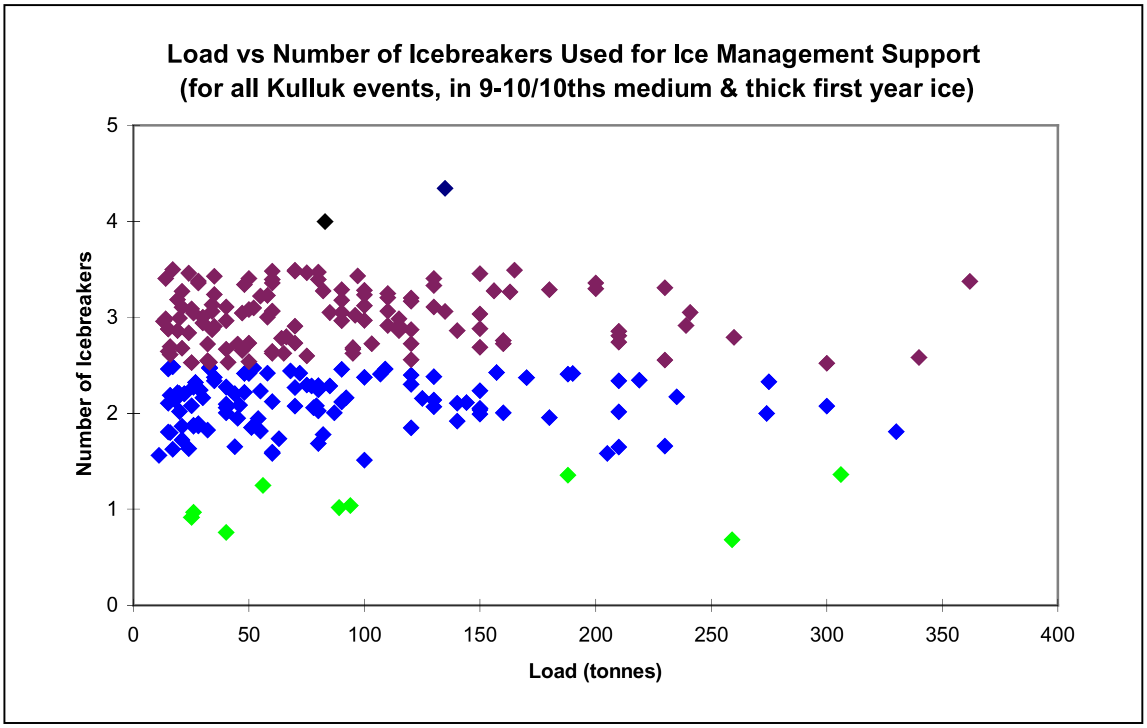


Figure 6.2: Load levels shown in relation to the number of icebreakers that were used to provide ice management support for Kulluk operations. This scatter plot includes events involving predominately medium to thick first year pack ice conditions, in concentrations of 9 - 10/10ths, which were often "heavy". Situations with ice pressure have been excluded from this plot.

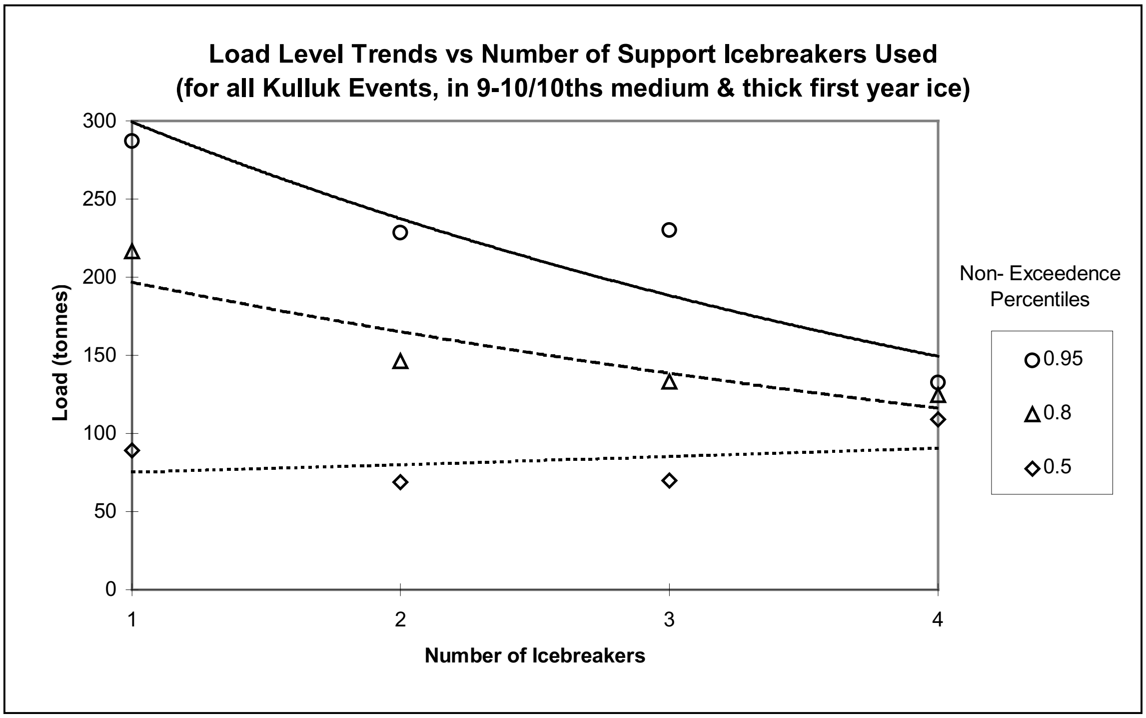


Figure 6.3: Load level trends as a function of ice management support in pack ice regimes 9 & 10, as suggested by the load data given above. This information should be appreciated as illustrating trends, but not providing relationships.

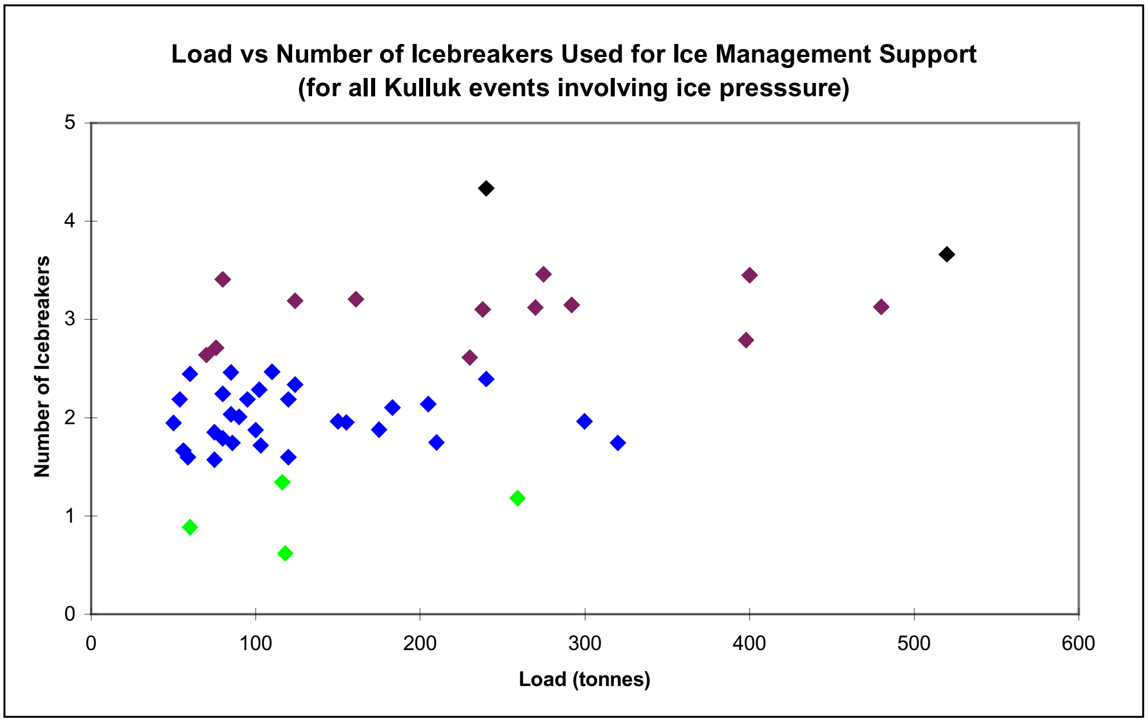


Figure 6.4: Load levels shown in relation to the number of icebreakers that were used to provide ice management support for Kulluk operations, in pressured ice situations. Associated pack ice thicknesses range from thin to thick ice.

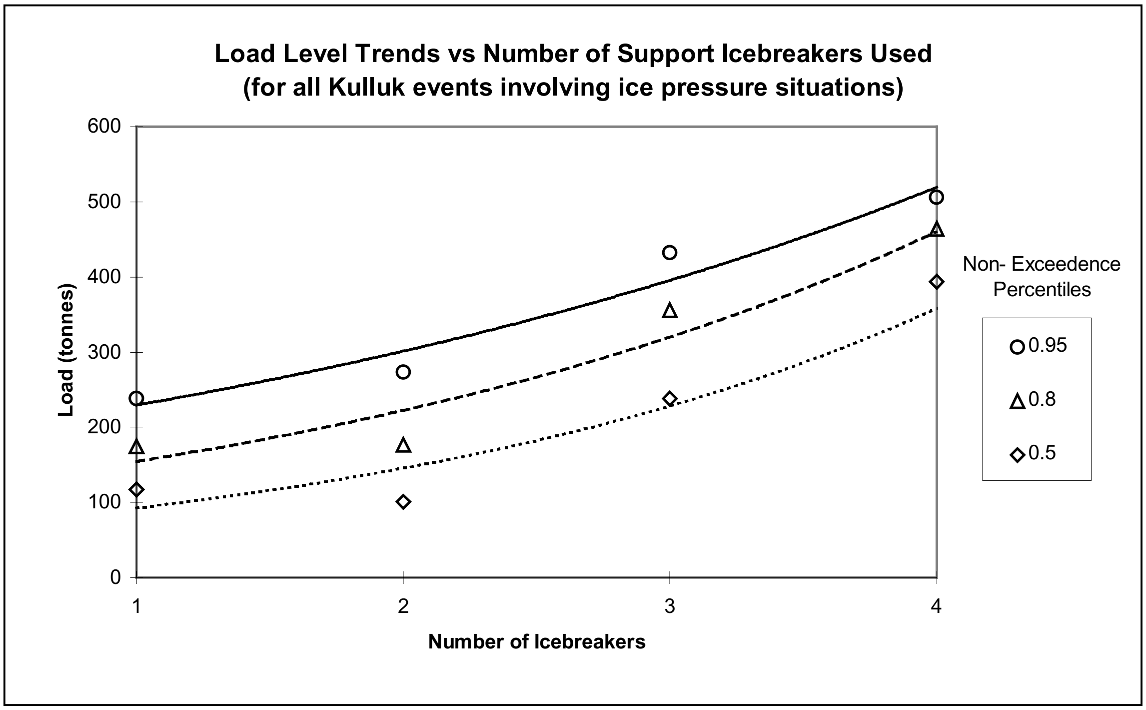
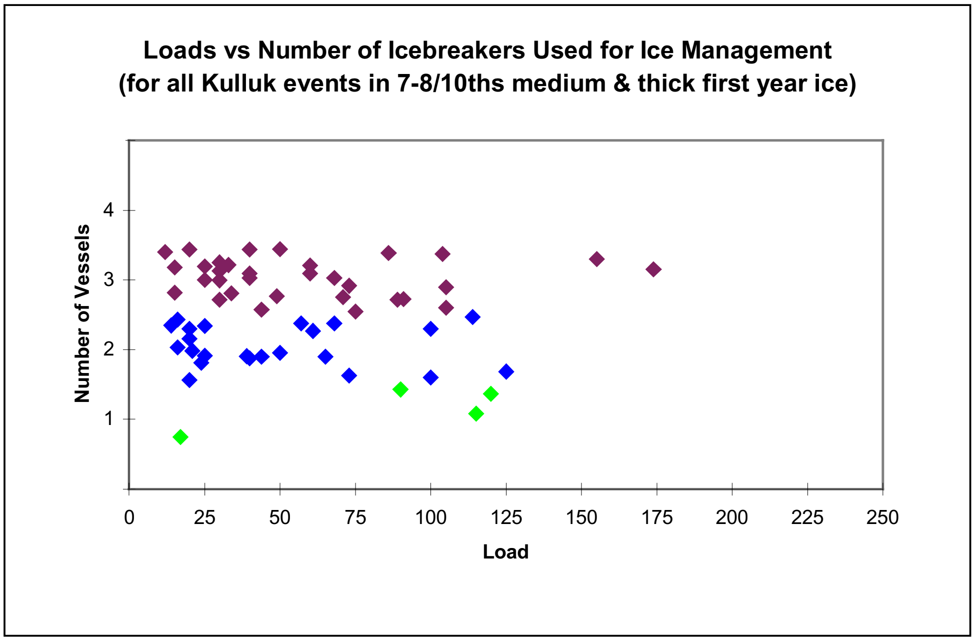


Figure 6.5: Load level trends as a function of ice management support in pressured pack ice (always a near continuous ice cover), as suggested by the load data given above. This data spans thin to thick ice interaction events involving pressure. Again, the information should be appreciated as illustrating trends, but not providing relationships.



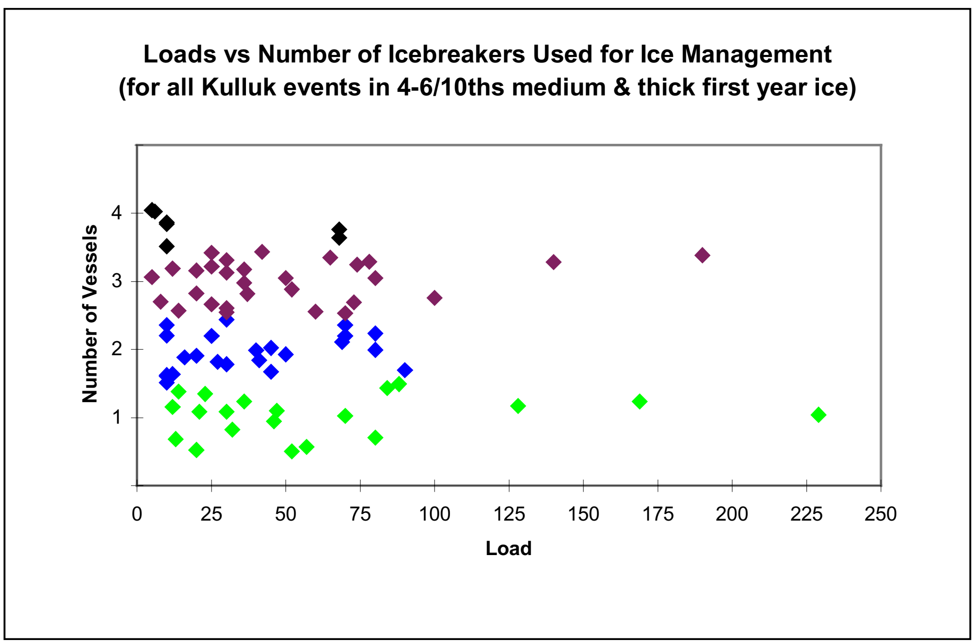
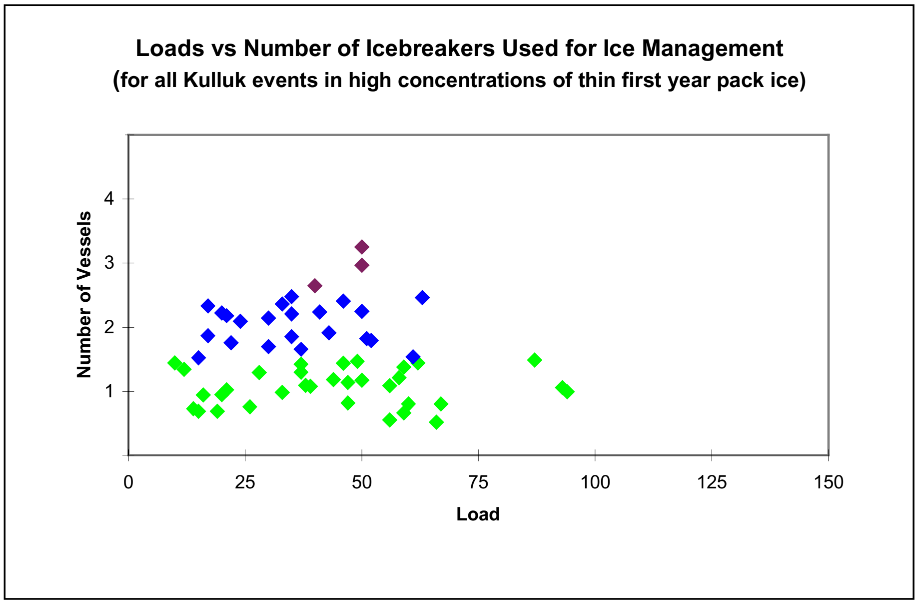


Figure 6.6: A scatter plot of load levels in relation to the number of icebreakers used for all Kulluk events in pack ice regimes 7 & 8 (upper) and 5 & 6 (lower). These represent 7 - 8ths concentrations of medium and thick first year ice types, and 4 - 6/10ths of these ice types, respectively.



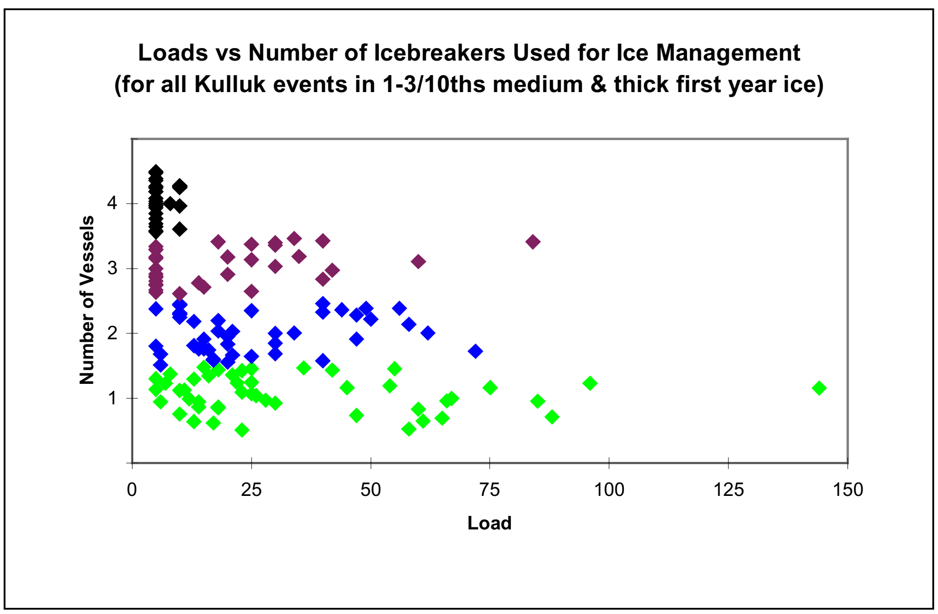


Figure 6.7: A scatter plot of load levels in relation to the number of icebreakers used for all Kulluk events in pack ice regimes 4 (upper) and 2 & 3 (lower). These regimes represent high concentrations of thin first year ice, and 1 - 3/10ths of medium and thick first year ice types, respectively.

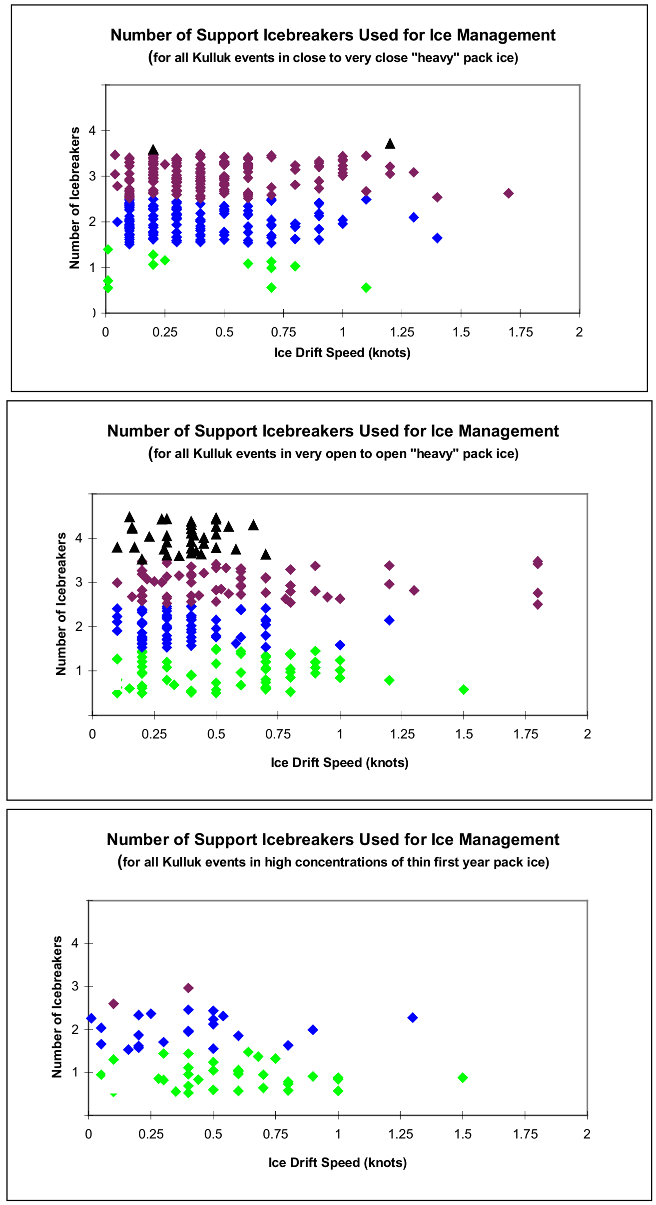


Figure 6.8: Scatter plots of the number of support icebreakers used in various pack ice conditions versus drift speed, for all events in the Kulluk data base except those with pressure. Here, the pack ice regimes in which operations were being carried out were combined into catagories involving close to very close “heavy” pack ice (7 - 9+/10ths, upper), very open to open “heavy” pack ice (1 - 6/10ths, middle) and high concentrations of thin pack ice (lower).

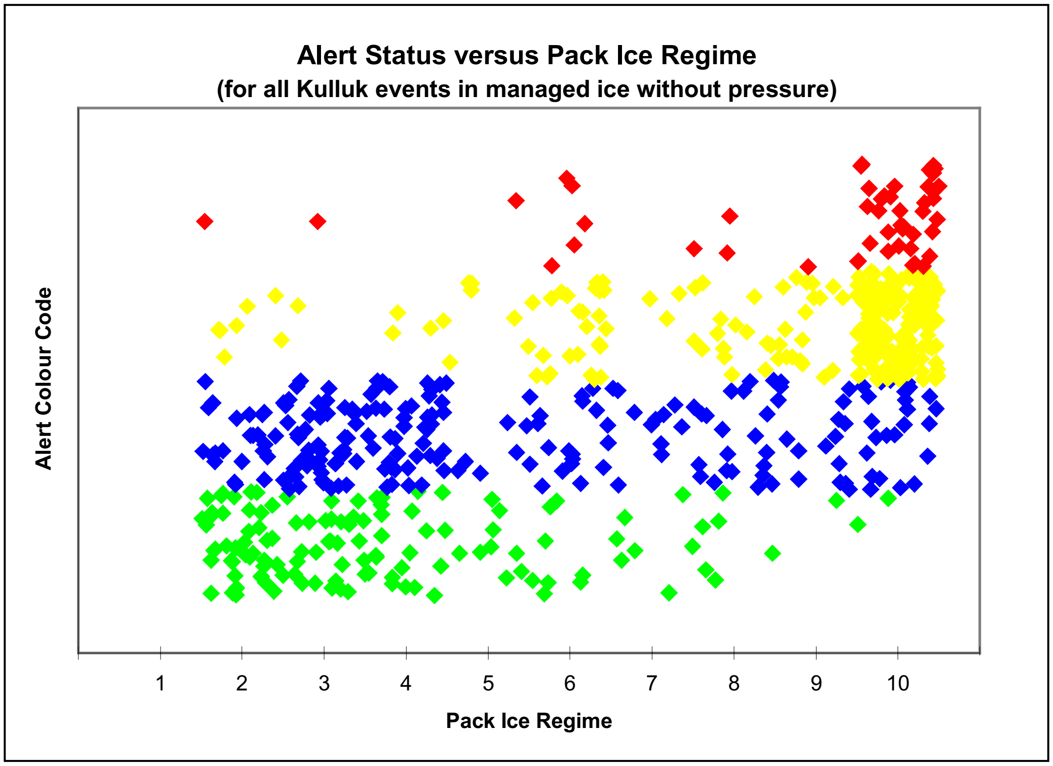


Figure 6.9: A scatter plot of the Kulluk's alert status during each event in the data base (excluding those involving ice pressure) as a function of the pack ice regime in which operations were being carried out. This scatter plot gives a feel for the risk levels experienced by the Kulluk in a broad range of pack ice situations. The colour of the data points indicates the alert colour code, with green, blue, yellow and red showing progressively higher levels of risk (here, the data points have been "artificially spread" by adding random numbers between ± 0.5 to integer values of 1,2,3,4 which were used to depict green, blue, yellow and red alerts).

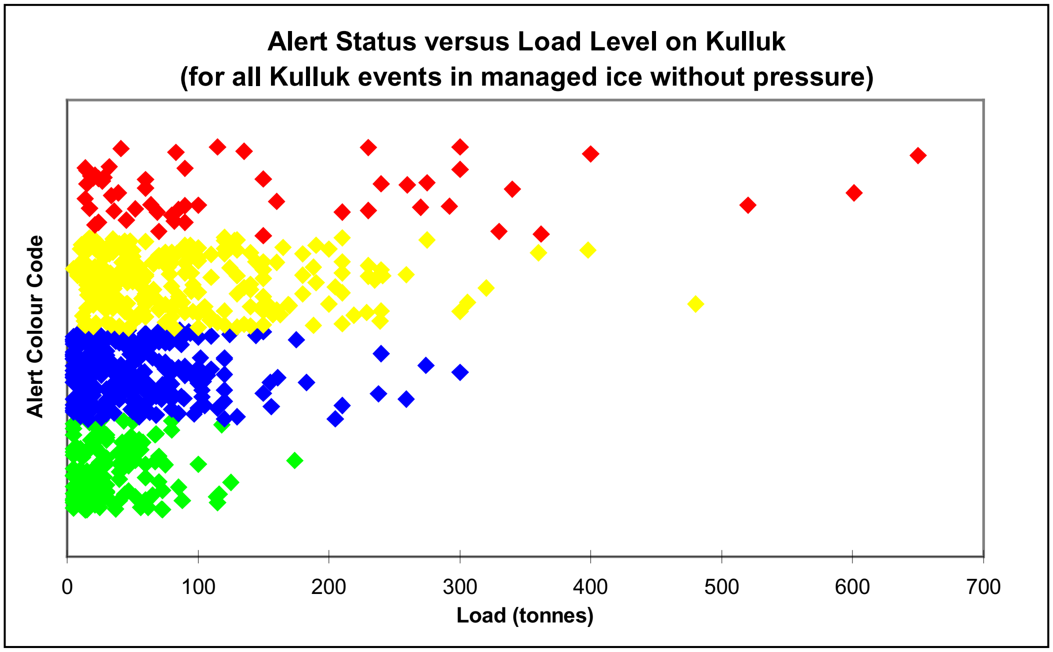


Figure 6.10: Scatter plot of alert status versus the measured load on the Kulluk for all events not involving ice pressure.

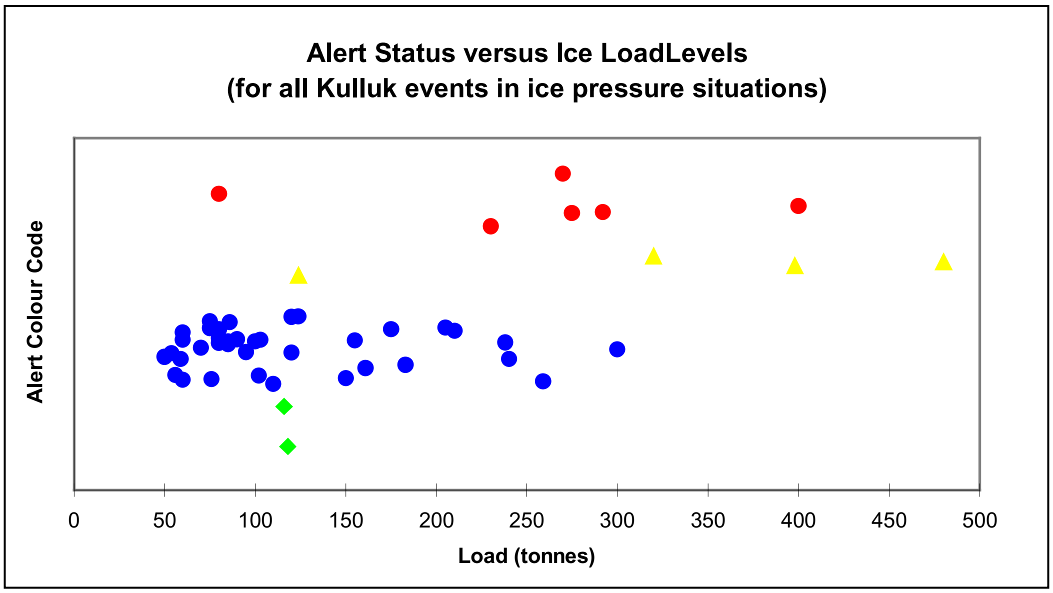
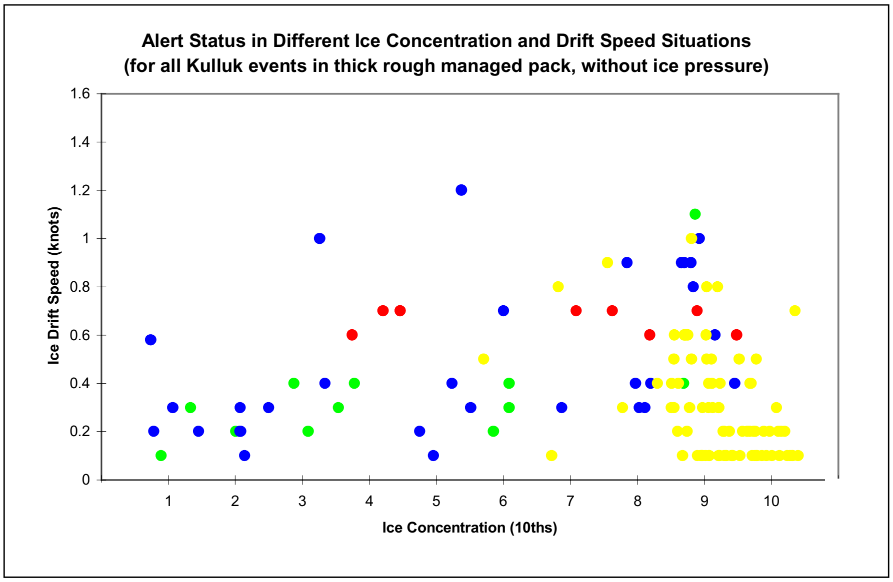


Figure 6.11: Scatter plot of alert status versus the measured load on the Kulluk for all events involving ice pressure.



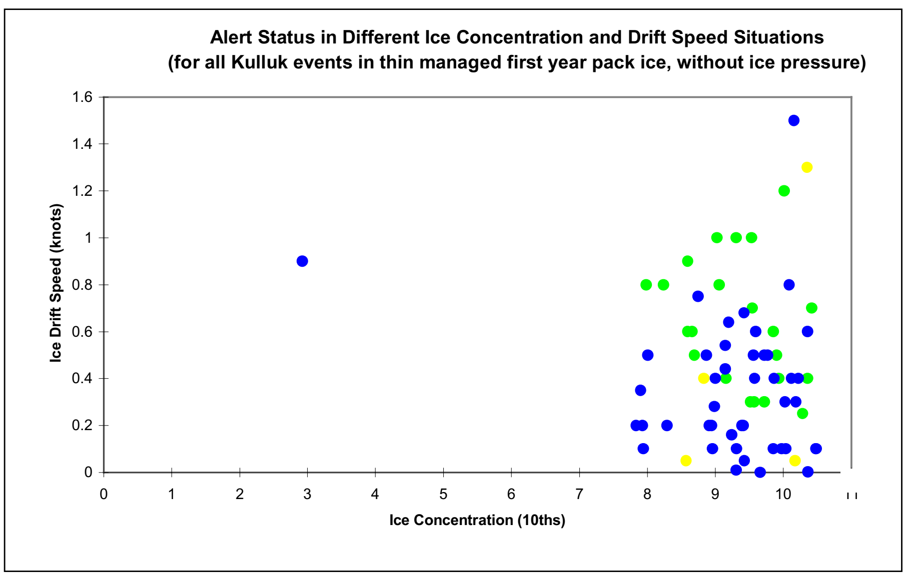


Figure 6.12: Scatter plots showing the Kulluk's ice alert status (by data point colours) in different ice concentration and drift speed situations. The upper plot is for "heavy" pack ice (thick rough first year ice, with some old floes) while the lower plot is for thin first year pack ice conditions. Both plots involve events where two icebreakers were used to provide ice management support.

7.0 Implications for Grand Banks Development Systems

7.1 General

The preceding sections have presented full scale load data that was acquired during Kulluk stationkeeping operations in Beaufort Sea pack ice conditions, along with related discussions about the ice management methods used and the "risk levels" encountered. In this section of the report, some of the key implications of this information are briefly highlighted in the context of Grand Banks development systems.

Companion reports (Wright et al, 1998, 1999) have treated the question of moored vessel stationkeeping in Grand Banks pack ice, together with expected load levels, in some detail. In terms of loads, these studies suggested that moored vessel operations in the type of pack ice is periodically encountered on the Grand Banks should be considerably less difficult than currently perceived, provided systems with reasonable in-ice capabilities and adequate levels of ice management support are used. Expected pack ice loads on representative FPSOs were estimated to be in the order of a few hundred to a thousand tonnes, which is well within the capability of their mooring systems. Similarly, expected load levels on tankers during loading operations in Grand Banks pack ice were estimated to be within acceptable bounds for typical mooring and loading arrangements, again providing tanker loading systems with reasonable in-ice capabilities and adequate ice management support are used.

Here, most of the views that were offered in these companion studies are reiterated, and a few additional comments given, on the basis of the new information presented in this report. In short, overall conclusions about the feasibility of moored vessel stationkeeping operations in Grand Banks pack ice conditions have not changed.

7.2 Grand Banks Pack Ice

As noted earlier, the Grand Banks is generally recognized as having one of the most hostile operating environments in the world, with high waves, icebergs and occasional pack ice being the primary factors of concern. However, it is the presence of icebergs and pack ice that make the area unique, since they present new challenges for Grand Banks development systems. Although the presence of icebergs is of highest concern for most Grand Banks development schemes, pack ice is also an important consideration. For example, any floating systems that may be used on the Grand Banks will unquestionably be exposed to pack ice occurrences over typical development project lifetimes. Pack ice intrusions are not seen annually but are usually experienced every several years, lasting anywhere from a week to a month, or more. On the northern and eastern parts of the Grand Banks, where new exploration plays are underway, these pack ice occurrences can be more frequent.

The pack ice that is found on the Grand Banks is normally quite thin, in the order of 0.3m to 0.7m, and is usually far from continuous in terms of its coverage. Ice concentrations in the order of 5/10ths to 8/10ths are most common, while floes sizes in the range of 30m in size are typical. However, more extreme pack ice conditions can also occur, which include slightly larger and thicker first year floes, pressure ridges and rafted ice areas, and small multi-year floe fragments. Icebergs and small glacial ice masses, which can also be contained within the pack, are the most formidable and hazardous ice features that can be encountered.

Statistics developed for current and potential development locations in the Grand Banks area (Wright et al, 1998) confirm that pack ice occurrences are not particularly frequent, and that the characteristics of the pack ice are not particularly severe. However, certain locations on the Grand Banks do experience an average of 20 to 30 days of pack ice coverage annually, with 50 to 70 days of pack ice coverage being seen at some of the more exposed sites in extreme years. Clearly, these pack ice occurrence levels could result in substantial levels of downtime for moored vessel systems with little or no "in-ice" operating capabilities.

For the purposes of the summary given here, the following Grand Banks ice conditions have been assumed as representative.

- typical ice concentrations in the order of 6/10ths to 8/10ths (or less), and occasional occurrences of ice concentrations in the 9/10ths range
- typical ice thicknesses in the order of 0.3m to 0.7m, and occasional occurrences of ice thicknesses in the 0.7m to 1.2m range

- typical ice floe sizes in the order of 30m, with occasional occurrences of larger ice floes, up to 100m or slightly more in extent
- drift speeds in the range of 0.75 m/sec and typically less, which are generally quite uniform in direction

7.3 Representative Systems

Representative systems have also been defined for the purposes of this summary, within the context of the following Grand Banks operating scenarios.

- FPSO stationkeeping in moving pack ice
- tanker loading at exposed sites in moving pack ice

Three moored vessels have been selected as being representative. These "typical vessels" are highlighted in Table 7.1, and are the same as those used for illustrative purposes in the last report (Wright et al, 1999). In terms of their choice, size was considered as the main variable. In this regard, the Terra Nova FPSO is compatible with relatively large oil field developments (≈ 400 millions bbls), while the Petrojarl 1 and Captain vessels are more representative for developments involving small to moderately sized oil fields (150 - 200 million bbls).

As shown in Table 7.1, these representative moored vessels range in size from 50,000 DWT to 160,000 DWT, with the Terra Nova FPSO being the upper bound case. The two smaller vessels are intended to represent lower bound and median cases, in terms of expected load levels from pack ice.

	Petrojarl 1	**Captain**	**Terra Nova**
Displacement	51,000 DWT	114,000 DWT	160,000 DWT
Length	209 m	215 m	280 m
Beam	32 m	38 m	45 m
Draft (loaded)	18 m	21 m	24 m
Hull Form		all have conventional open water hull forms	
Storage	190,000 bbls	550,000 bbls	960,000 bbls
Process	50,000 BOPD	80,000 BOPD	125,000 BOPD
Mooring System	external turret	internal turret	internal turret
# of lines	8	6	6
# of risers	8	12	20
mooring capacity	1000 tonnes	1500 tonnes	2000 tonnes
Current Use	Blenheim - North Sea	Captain - North Sea	Terra Nova (future)

Table 7.1: Representative moored vessels.

In addition to giving information on the size of these vessels, Table 7.1 also provides some information about their mooring and riser systems. It may be seen that each of these FPSO vessels has a turret which houses its mooring and riser systems. These turrets allow the vessels to vane into the direction of oncoming environmental forces, thereby reducing mooring loads and FPSO response motions. In essence, this makes them similar to the Kulluk in terms of their ability to accept ice action in any direction. It may be seen that the mooring systems of these vessels are also very capable, with the capacity to withstand forces that are in the 1000 tonne to 2000 tonne range, with acceptable vessel offsets and individual line tensions. From a tanker loading perspective, vessel sizes that are in the same range as these FPSOs have also been assumed.

7.4 Estimated Load Levels

Estimates of expected load levels on these types of moored vessels were provided in the last report (Wright et al, 1998), for both typical and severe Grand Banks pack ice conditions. These estimates were based on the original full scale Kulluk load data and implicitly assumed that a reasonable level of ice management support was available. They were developed by applying the following analysis procedure, which is outlined in more detail in Appendix 1. .

- "correction factors" were first calculated to transform the full scale Kulluk load data into "equivalent loads" on the three representative vessels. This calculation is based on a method developed from full scale ship resistance data in ice (Keinonen et al, 1996), which accounts for differences in the size and hull form of each vessel.

- the type of ice interaction scenarios and accordingly, the full scale Kulluk load data sets that are most appropriate for the "Grand Banks moored vessel consideration" were then selected, namely:

  - the full scale loads that were measured in well managed ice conditions with good ice clearance (see Figure 2.5), which are comparable to most of the pack ice interaction situations expected on the Grand Banks

  - the full scale loads that were measured in tight managed ice conditions with poor ice clearance (see Figure 2.6), which conservatively, are comparable to most of the severe pack ice interaction situations expected on the Grand Banks

- the "upper bound lines" for these full scale Kulluk load data sets, in combination with the correction factors for vessel size and shape, was then used to estimate load levels on the three representative vessels, across the range of pack ice thicknesses expected on the Grand Banks

In Section 4, the high level of compatibility between the new Kulluk load event data provided in this report, and the original Kulluk load data, was clearly demonstrated. Because the two data sets are basically “one in the same”, there is no basis for changing any of the load level estimates already developed for moored vessels in Grand Banks pack ice conditions. In fact, the addition of the new Kulluk load event data reinforces these estimates, since they are now based on the data from almost twice as many full scale loading events. Table 7.2 provides a summary of the load level estimates that have been made for the three representative moored vessels, in the type of pack ice conditions expected on the Grand Banks. Again, these estimate assume a reasonable level of ice management support. With regard to the range of expected load levels that are shown in Table 7.2, the following points should be noted.

- these loads levels are based on upper bound fits to the full scale data and in this sense, are quite conservative

- recognizing the type of pack ice conditions that are encountered on the Grand Banks, including typical ice concentrations:

    - the load levels given for the good ice clearance cases are the most reasonable to expect
    - these loads are in the range of a few hundred tonnes and are quite small when compared to the capability of an FPSO’s mooring system

Pack Ice Thickness & Movement Conditions	**Peak Loads on Representative FPSO Vessels (tonnes)**		
With Good Ice Clearance Around the Vessel	***Petrojarl 1***	***Captain***	***Terra Nova***
Normal (0.3m - 0.7m)			
- constant drift direction	160 - 210	180 - 250	220 - 300
- typical drift direction change	220 - 280	250 - 350	350 - 480
- rapid drift direction change	300 - 400	360 - 500	480 - 660
Severe (1.0m - 1.2m)			
- constant drift direction	250 - 280	300 - 330	350 - 390
- typical drift direction	300 - 380	420 - 460	560 - 620

Pack Ice Thickness & Movement Conditions	**Peak Loads on Representative FPSO Vessels (tonnes)**		
change			
- rapid drift direction change	480 - 530	600 - 660	770 - 860
With Poor Ice Clearance Around the Vessel	***Petrojarl 1***	***Captain***	***Terra Nova***
Normal (0.3m - 0.7m)			
- constant drift direction	430 - 570	500 - 650	600 - 780
- typical drift direction change	580 - 770	700 - 910	960 - 1250
- rapid drift direction change	820 - 1080	1000 - 1300	1320 - 1720
Severe (1.0m - 1.2m)			
- constant drift direction	660 - 730	760 - 840	920 - 1010
- typical drift direction change	890 - 990	1060 - 1180	1470 - 1620
- rapid drift direction change	1250 - 1390	1520 - 1680	2020 - 2220

Note: - ice management can be used to clear any ice that may be loading the "longside" of an FPSO in poor ice clearrance, changing drift direction situations, and reduce loads to much lower levels
- since tankers will be in the same general size and shape range as the FPSO vessels considered here, load levels on them in equivalent pack ice situations should be quite similar.

Table 7.2: Expected load levels on representative FPSO vessels, conservatively estimated from the full scale Kulluk load event data base.

- the load levels that are shown for "tight" pack ice with poor clearance, particularly in changing drift direction situations, are quite substantial when compared to the FPSO mooring system capacities, or mooring limits on a tanker loading operation

- although it is unlikely that these types of situations will be seen, good ice management can be used to loosen and clear ice around an FPSO or a loading tanker, and in turn, substantially reduce load levels ("back down" to those seen with good ice clearance)

Here, it should also be noted that a pragmatic "double check" on these load level estimates has been carried out, using the Kulluk load data expressed as a function of pack ice regime. Based upon the type of load data summary given in Figure 4.6, and reasonable equivalences in pack ice regimes, similar load level estimates can be obtained. Related details are not given here, but are summarized in Appendix 1.

7.5Ice Management and Ice-Related Risks

Information about the ice management systems that were used to reduce ice load levels on the Kulluk and, to mitigate ice related risks, was presented in Sections 5 and 6. Obviously, this information is specific to the Kulluk system and to its operations in the Beaufort Sea, since it reflects:

- the pack ice conditions encountered
- the in-ice operating capabilities of the Kulluk
- the type and number of support icebreakers used

Despite the specific nature of the Kulluk data, the experiences that were gained with this vessel can be applied more generically, in combination with reasonable judgements, for other ice-infested areas like the Grand Banks. Here, the most basic message to offer is that moored vessel stationkeeping operations have been carried out in pack ice conditions before, on a routine basis, with safety and efficiency, and should be "doable" in most ice covered areas. However, the use of ice capable equipment and sound in-ice operating practices is a clear prerequisite.

In this regard, the following views are given.

Ice Management Systems

- ice management systems that, in concept, are similar to those used to support the Kulluk, will be an important element of any moored vessel stationkeeping operation in pack ice conditions. The basic components of this type of system should include:

- *an ice monitoring and forecasting component*. In relation to this particular area, some of the key considerations are:

    - the need for an all weather, day/night ice detection capability
    - the importance of an appropriate blend of ice monitoring "coverage frequencies and detection resolutions", on regional and local scales
    - the need for enough ice detection resolution to clearly identify features of concern within the pack ice (at least locally), in particular, icebergs, small glacial ice masses and remnant old ice floes on the Grand Banks
    - provision for confirmatory visual input from airborne recces and support vessel observations, to "check-out" the oncoming pack ice, and to more directly assess its manageability
    - the need for timely, well communicated and reliable information from any ice monitoring and forecasting systems used

- *a performance monitoring system onboard the moored vessel*. For stationkeeping operations in pack ice (ie: not the design issue of local loads on the vessel's hull structure), key considerations include:

    - appropriate measurements of mooring line tensions, global load levels and vessel response motions
    - calibration of any line tension and overall system load measurements, to ensure their accuracy
    - the operational need for real time displays of line tensions, mooring loads and response motion onboard the moored vessel, and how best to "show and use" this information
    - efficient recording of ice event data, for future use in assessing operating limits and improving the knowledge base for "next generation" designs

- *well defined ice alert procedures*. These are clearly a central element of any ice management system, in terms of the safety of operations in ice. On the Grand Banks, there is a strong experience base with the use of alert systems for icebergs.

The ice alert concepts already in use should simply be extended for moored vessel stationkeeping operations in moving pack ice.

- *an effective ice management support vessel system*. Here, key considerations are:

  - the number and type of support vessels needed
  - the appropriate ice class (ie: hull ice strengthening) and powering of these vessels for their intended ice management roles
  - the capabilities of these support vessels in terms of breaking and clearing ice around a moored stationkeeping vessel

- *integration in the use of the foregoing ice management system components*. In this area, key considerations include:

  - specific and "fully defined" communication, coordination and evaluation procedures for all aspects of the integrated ice management activity
  - well defined roles, responsibilities and accountabilities for these activities

Ice Management Support Vessels

- the type of "highly capable" icebreaker system that was used to manage ice and reduce load levels on the Kulluk should not be required to support moored vessel operations in the Grand Banks area, since pack ice conditions in this region are considerably "easier". Related comments and views are highlighted as follows.

  - when it occurs, the pack ice that spreads out onto the Grand Banks comes in a the form of "a naturally managed ice cover", with typical floes sizes in the order of 30m. This floe size range is about the same as targets for managed ice piece sizes around the Kulluk in the Beaufort Sea.

  - the pack ice that normally occurs on the Grand Banks is fairly thin and "loose", with typical thicknesses of 0.3m to 0.7m and concentrations of less than 9/10ths

These types of conditions were associated with good ice clearance around the Kulluk in the Beaufort Sea and, an “easy stationkeeping” situation.

- it is likely that two ice capable vessels will be adequate to support moored vessel operations in most Grand Banks pack ice conditions. In this regard:

    - two vessels offer redundancy and provide synergy, for ice management activities
    - support vessels with adequate levels of hull ice strengthening are needed, to ensure they can carry out their ice management operations in a prudent manner
    - based on previous experience with the Kulluk, ice management techniques oriented towards ice clearance rather than icebreaking will be of highest importance on the Grand Banks, since most of the pack ice is naturally prebroken

Ice Related Risks

- given the experiences gained during Kulluk operations in Beaufort Sea pack ice, any ice-related risks that are associated with moored vessel stationkeeping in Grand Banks pack ice should be viewed as manageable, providing ice capable equipment and appropriate in-ice operating procedures are used. In this regard:

    - the Kulluk experience and load and alert data suggests that safety and efficiency in floating system operations in Grand Banks pack ice should be quite achievable
    - in addition to good equipment and procedures, well trained and well experienced operating personnel will be be a key ingredient for success
    - potential contact with icebergs and “sizeable” small ice masses drifting within the pack will represent the “highest risk” situations
    - the potential effects of non-colinear forces from ice, winds, waves and currents on “vaning” vessels should be considered

8.0 Summary

In this report, the question of moored vessel stationkeeping in moving pack ice conditions has been addressed, on the basis of full scale experience with Kulluk operations in the Beaufort Sea. As part of this work, a data base which documents full scale ice load levels on moored vessels has been almost doubled in size, with additional Kulluk load event data. In addition, some of the more operationally oriented information about ice management support activities and perceived risk levels (alerts) has been blended with it.

This data base has been exercised to highlight key features of the Kulluk information, and to illustrate salient points. Experiences gained during the Kulluk's operations have also been described, including the types of ice management methods employed to reduce load levelst, and mitigate ice related risks. In this regard, it is important to note that ice loads are only one part of the moored vessel stationkeeping consideration. The use of ice capable equipment, sound ice management methods, and well defined in-ice operating procedures are all essential parts of the equation for safe and effective operations with moored vessels in pack ice. Key results of this study are briefly highlighted as follows.

Kulluk Event Data

- a unique data base that contains an unparalleled source of "real world" information about full scale loads on moored vessels across a wide range of pack ice conditions has been significantly extended. This data is important not only for future development activities on the Grand Banks, but also for other ice infested regions of the world where moored vessel stationkeeping operations are being considered.

- this load event data, which has been extracted from information acquired during Kulluk operations in the Beaufort Sea, includes almost 700 documented full scale ice load events. For each one of these events, the data base includes information regarding:

  - the ambient pack ice conditions and drift speeds encountered
  - the levels of ice management support used
  - the ice load levels experienced

- the ice alert status in-place, as an indicator of risk

- the data base remains proprietary to NRC as custodians, and to Gulf Canada as owner of the data. However, the key features of the Kulluk data, as well as its main implications for future Grand Banks floating development systems, have been presented in the report.

- as part of this study work, the data base has been exercised to evaluate ice load levels, perceptions of risk, and the associated trends that are suggested, as a function of different pack ice regimes, ice parameters, and levels of ice management support. The following types of scatter plots have been provided, to summarize the Kulluk data and to illustrate salient points. These scatter plots show clear and logical trends.

  - loads in different pack ice regimes
  - loads in managed ice conditions with good clearance
  - loads in tight managed ice conditions and in ice pressure
  - ice management levels used in different pack ice regimes
  - loads in relations to ice management levels
  - alert levels (perceived risk) in relation to loads
  - alert levels in relation to ice management support

- information has also been provided about the ice management systems used to support Kulluk operations, and the specific ice management techniques employed. Although this information is Kulluk specific, most of the lessons learned are transferable to moored vessel operations in other ice infested areas. In this regard, the key components of any composite ice management system should include:

  - an ice monitoring & forecasting system
  - a performance monitoring system
  - an ice alert system
  - an icebreaker support system
  - well defined ice management procedures
  - well defined lines of communication, responsibility and authority

  These basic ice management system components are viewed as mandatory, for moored vessel stationkeeeping operations in Grand Banks, pack ice or in-ice operations in any other ice infested areas of the world.

Implications for Grand Banks Systems

The Kulluk event data that is given in this report has been used as a basis for providing some perspectives about moored vessel operations in Grand Banks pack ice conditions. For the purposes of this work, several representative moored vessel systems have been defined, within the context of the following development scenarios.

- FPSO stationkeeping operations in moving pack ice
- tanker loading operations in pack ice

Expected load levels on these vessels have been shown to be in the range of a few hundred tonnes for realistic scenarios, depending upon ice thickness, ice movement and ice clearance conditions. Since these load levels are well within the capability of most mooring systems, the work suggests that moored vessel stationkeeping operations in the type of pack ice conditions that are periodically encountered on the Grand Banks should be less difficult than is currently perceived, providing systems with reasonable in-ice capabilities and adequate levels of ice management are used. A few related comments are given as follows.

- it is likely that two vessels with adequate levels of ice strengthening will be sufficient for effective ice management support around Grand Banks floaters in current locations of interest. However, more substantial levels of ice management support may be required may be required as future operations move into heavier pack ice areas, towards the north.

- potential pack ice-related risks on the Grand Banks can be mitigated, and should be quite manageable, with appropriate operating and ice management procedures

- ice management support, oriented towards ice clearance rather than icebreaking, will likely be of highest importance since most Grand Banks pack ice is “naturally managed” into small floes by the environment

- safety and efficiency in floating system operations in Grand Banks pack ice should be quite achievable

- potential contact with any icebergs or "sizable" small ice masses drifting within the pack represents the highest risk situations

Recommendations

This report has presented information about moored vessel stationkeeping operations in moving pack ice, based on Kulluk experiences in the Beaufort Sea. Recommendations for future work, with particular emphasis on future Grand Banks developments, are outlined as follows:

- as the highest priority, documentation of moored vessel performance in pack ice in full scale, with different levels of ice management support. Realistic opportunities to pursue this full scale data acquisition area include performance monitoring of:

  - FSO operations around the Molikpaq off Sakhalin Island, in break-up and freeze-up pack ice conditions
  - FPSO operations at Terra Nova, when pack ice intrusions occur
  - tanker loading operations at Hibernia, when pack ice intrusions occur

- consideration of the effects of non-colinear environmental forces on "long shipshaped" moored and vaning vessels, including the potential loads from ice, waves, winds and currents

- more serious consideration of the capabilities of the support vessels that are or will be realistically available on the East Coast, to provide appropriate levels of ice management support for Grand Banks systems

- inclusion of the results of this study into new initiatves regarding offshore design codes, relating to the use of moored vessel systems on the Grand Banks and in other ice infested areas

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Appendix 1

Methodology for Applying Kulluk Load Data to Vessels of Different Sizes and Hull Forms

Kulluk Load Data "Conversion"

In-ice ship resistance prediction formulae have been developed (Keinonen et al, 1989, 1991, 1996) from analyses of ship resistance data in level ice, which include parametric influences for differing vessel dimensions, hull forms, hull surface conditions, ice strengths and ambient temperatures. These parametric dependencies, which have been used to "convert" the full scale Kulluk load data to vessels of different size and hull form, are given as follows.

Ship resistance in ice is proportional to:

$$(C_s * C_h * B^{0.7} * L^{0.2} * D^{0.1})$$
$$* (1- 0.0083 * (T + 30)) * (0.63 + 0.00074\ \sigma_f)$$
$$* (1+ 0.0018 * (90- \iota)^{1.6}) * (1+ 0.003 * (\varphi-5)^{1.5})$$

where**:**

C_s	=	1.0 for saline, 0.85 for brackish, and 0.75 for fresh water conditions.
C_h	=	1.0 for Inerta coating and 1.33 for bare steel
L	=	load waterline length (m)
B	=	ship beam (m)
D	=	ship draft (m)
ι	=	bow flare angle averaged over the beam.
φ	=	bow buttock angle averaged over the beam
σ_f	=	flexural strength of ice (kPa)
T	=	ice surface or air temperature in degrees Celsius

An example of how these dependencies have been used to convert the Kulluk data into load estimates for other vessel sizes and shapes is given as follows, for the Terra Nova FPSO. Since the Kulluk is central, this vessel has been treated as a "ship" with the following parameter values.

L	=	70m load waterline length (m)
B	=	70m ship beam (m)

D	=	11.5m ship draft (m)
ι	=	75 degrees bow flare angle averaged over the beam.
φ	=	23 degrees bow buttock angle averaged over the beam

The corresponding ship parameter values assumed for the Terra Nova FPSO vessel are:

L	=	280m waterline length (m)
B	=	45m beam (m)
D	=	24m draft (m)
ι	=	20 degrees bow flare angle
φ	=	70 degrees bow buttock angle

The "size factor" that can be derived between the Kulluk and FPSO is given as:

$$B^{0.7} * L^{0.2} * D^{0.1}$$

Kulluk = $(70)^{0.7} * (70)^{0.2} * (11.5)^{0.1}$ = 58.4
FPSO = $(45)^{0.7} * (280)^{0.2} * (24)^{0.1}$ = 61.9

The "shape factor" that can be derived between these two vessels is given as:

$$(1+ 0.0018 * (90- \iota)^{1.6}) * (1+ 0.003 * (\varphi-5)^{1.5})$$

Kulluk = $(1+ 0.0018 * (90-75)^{1.6}) * (1+ 0.003 * (23-5)^{1.5})$ = 1.4
FPSO = $(1+ 0.0018 * (90-\iota)^{1.6}) * (1+ 0.003 * (\varphi-5)^{1.5})$ = 6.7

By combining the size and shape factors for the Kulluk and FPSO, we get:

Kulluk = 58.4 x 1.4 = 81.8
FPSO = 61.9 x 6.7 = 414.7

The factor that can then be used to convert Kulluk loads to FPSO load estimates is given as:

Loads on the Kulluk to loads on the FPSO = 414.7 / 81.8 = 5.07

Note that these factors exclude the terms that are required to normalize the load data for ice strength and ice friction effects.

The factors that have been calculated in this manner, then used to apply the full scale Kulluk load data to the FPSO (and tanker loading) cases presented in Section 7 are as follows.

	Loads on Kulluk → Loads on Vessel
Terra Nova FPSO	5.1
Petrojarl 1 FPSO	3.7
Captain FPSO	4.3

A straightforward application of these factors, with the Kulluk load versus pack ice regime data (Figure 4.9), is as follows.

- pack ice regime 4 is very similar to most pack ice conditions on the Grand Banks
- peak ice load levels on the Kulluk in pack ice regime 4 are about 100 tonnes
- using the factors shown above, the peak FPSO ice load estimates are:

Terra Nova FPSO	510 tonnes
Petrojarl 1 FPSO	370 tonnes
Captain FPSO	430 tonnes