Evaluation of full-scale data for moored vessel stationkeeping in pack ice

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Evaluation of Full Scale Data for Moored Vessel Stationkeeping in Pack Ice

(With Reference to Grand Banks Development)

submitted to

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

PERD/CHC Report 26-200

by

B. Wright & Associates Ltd.

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Executive Summary

This report presents the results of a PERD sponsored study that addresses the question of loads on moored vessels in moving pack ice conditions, with particular reference to floating development systems on the Grand Banks. In terms of scope, the report includes:

- a review of the full scale data that is available regarding loads on moored vessels in pack ice, including:

    - information that was obtained during operations from the Kulluk and Canmar drillships in Beaufort Sea ice conditions
    - relevant information that was obtained from various vessel performance trials and other ship operating experiences in ice

- the development of a full scale data set from selected "events" that gives quantitative information about loads on moored vessels in different pack ice conditions

- an evaluation that summarizes the full scale load information in the form of combined scatter plots, and ties all of the data together in the context of expected load levels on moored vessels in pack ice

- a comparison of the full scale load data with relevant information from a companion PERD project (Comfort et al, 1999), which deals with moored vessel model tests

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

Some of the key results that have been generated by this study are briefly highlighted as follows.

Full Scale Data Set

A unique data set has been developed that contains an unparalleled source of "real world" information about full scale loads on moored vessels in a wide range of moving pack ice conditions. This data set is important not only for future development activities on the Grand Banks, but also for any other ice infested regions of the world where moored vessel stationkeeping operations are being considered. By way of summary:

- information that was acquired in conjunction with drilling operations from the Kulluk comprised the majority of the data set, and includes 384 different loading events. This data forms the "backbone" of the work, because of both its quality and quantity.

- relevant information from vessel performance trials and other in-ice ship operations is not particularly plentiful, with only 26 “ship events” being contained in the full scale data set. However, these ship entries are a meaningful component of the data set, since comparisons with the Kulluk loading information shows that all of the data ties together sensibly, and forms a consistent and credible pattern.

- although Canmar gained a great deal of experience with their Beaufort Sea drillships, there was very little documentation around their operations, particularly with regard to the load levels experienced by these moored vessels in ice. Since there is basically no quantitative information from Canmar’s drillships that is either available or can be meaningfully used in this study, this data source has necessarily been excluded.

Evaluation of Full Scale Data

The full scale data set has been “exercised” in this study, to evaluate the loading levels and trends that it suggests as a function of different ice parameters. Scatter plots of the Kulluk data are given for the following ice and ice interaction situations.

- loads in level unbroken ice
- loads in unbroken ridges
- loads in managed ice with good clearance
- loads from floe impacts
- loads in “tight” managed ice and in “ice pressure’

Information about the nature of these types of loading events on the Kulluk is also provided, which includes “rise times” to peak loads, peak to mean load ratios, and event durations.

This evaluation of the full scale Kulluk load data shows very clear and logical trends. As noted above, comparisons between the Kulluk and ship data are also made, which indicate that all of the full scale load information ties together well, and forms a consistent and credible pattern.

Comparison with Model Tests

The full scale load data has also been compared with the results of relevant physical model tests that have been carried out with moored vessels in moving ice conditions. Comparisons have been made for level ice, ridge and managed 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 is shown between the majority of the model test and full scale load measurements is surprisingly good, for equivalent ice interaction situations. In most cases, the model test results tend to lie towards the upper end of the full scale load data. This however is not uncommon, based on comparisons between model test and full scale load information for other types of offshore structures.

Implications for Grand Banks Developments

The full scale data set has also been used to obtain some perspective about expected load levels on moored vessels in Grand Banks pack ice conditions. This “data set application” serves two purposes. Firstly, it provides an example of how the full scale data can be used and secondly, it presents relevant loading information for typical Grand Banks systems. For the purposes of this work, several representative vessels 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 are shown to be in the range of a few hundred to a thousand tonnes, depending upon ice thickness, ice movement and ice clearance conditions. Since these load levels are within the capability of most mooring systems, the work suggests moored vessel operations in the type of pack ice conditions that are 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 are used. However, it is also recognized that the occurrence of growlers, bergy bits and icebergs within the pack, as well as combined ice and wave conditions, will present new challenges.

Table of Contents

Appendix 1: Kulluk Ice Management Strategies

Appendix 2: Notes on Ship Events from Canmar's JIP Study

Appendix 3: Example of Ship Data Standardization Procedure

1.0 Introduction

1.1 General

The Grand Banks region, which lies off Canada's East Coast, has proven reserves of 1.5 billion barrels of oil and 1 trillion cubic feet of gas, and estimated recoverable reserves that are far in excess of these numbers. This region is well recognized internationally, as one of the most important "offshore oil and gas theatres" that has emerged in recent years. Oil production from the Hibernia field has been underway for almost two years and the next major development project, at Terra Nova, is scheduled to be on stream in the year 2001. These developments are important in their own right, but have also led to a general renewal of industry interest in the Grand Banks. Delineation drilling programs are now being carried out at earlier discoveries such as the Whiterose, Hebron and Ben Nevis prospects, and new exploration initiatives are also underway. These activities should give rise to a variety of new development opportunities, with a progressive expansion in the overall scope of Grand Banks operations expected over the upcoming years.

Most of the development approaches that are being considered for small to moderately sized oil fields on the Grand Banks involve the use of floating production concepts, similar to the FPSO system that will be employed at Terra Nova. Developments that are based on the use of bottom founded structures like the Hibernia GBS are less likely, unless extremely large oil fields are discovered in future years. To be effective, floating production systems will have to stationkeep in a safe and efficient manner in most of the storm wave, iceberg and pack ice conditions that can be encountered on the Grand Banks. Otherwise, related downtime could have a significant impact on the operability and economic viability of the floating production approach. Although fixed structures are much less susceptible to downtime because of these environmental influences, the tanker loading operations that are carried out from them can be adversely effected by the occurrence of storm waves, icebergs and pack ice. From a tanker loading perspective, for either fixed or floating development systems, prolonged periods of downtime could lead to major delays in production, depending upon the amount of oil storage that is available on a particular platform.

Pack ice occurrences on the southern Grand Banks are relatively infrequent in comparison to storm wave and iceberg events. However, the question of vessel stationkeeping and tanker loading operations in pack ice is an important issue for the area (Wright et al, 1997), because of its potential impact when it does occur. It should also be recognized that this question will become progressively more important as activities move northwards from the Jean d'Arc Basin, where most of industry's interest is currently focused, into areas where pack ice is seen more frequently.

In a recent PERD report (Wright et al, 1998), the question of moored vessel stationkeeping in Grand Banks pack ice was reviewed in some detail. In this report, examples of the type of full scale information that has been gathered, primarily from moored vessel operations in the Beaufort Sea, were used to address the issue. As part of the study, it was also noted that there was "a wealth of full scale data", particularly on load levels in different ice conditions, that would be of high value in terms of:

- developing a systematic and generally applicable data set regarding the range of full scale ice loads that should be expected on moored vessels in moving pack ice

- further evaluating the question of moored vessel stationkeeping operations in Grand Banks pack ice conditions, and in other ice infested areas of the world

NRC, on behalf of PERD, has contracted B. Wright & Associates Ltd. to extend this earlier study, by more fully documenting some of the full scale data that is available and further evaluating some of its implications for moored vessel stationkeeping operations in Grand Banks pack ice. The results of this work, which was undertaken in association with R. P. Browne Consultants, are presented in the remainder of this report.

1.2 Objectives

The primary objective of this study is to develop a data set that contains full scale load measurements on moored vessels in ice, and can be used to investigate the question of vessel stationkeeping operations in a wide range of moving pack ice conditions. In this study, this type of data set has been developed and the full scale load data within it evaluated. The data set also been exercised, at least in a preliminary manner, to illustrate that expected load levels on moored vessels in Grand Banks pack ice should be considerably lower than may be currently perceived, providing marine systems with reasonable in-ice capabilities are used.

The more specific objectives of the study are:

- to review historical information that is available regarding the performance of the Kulluk and Canmar drillships in Beaufort Sea pack ice conditions, and select events that provide quantitative information on mooring loads in different ice conditions

- to extract relevant information for each event, including:

    - the characteristics of the vessel and its mooring system
    - the time of each event, and the ice conditions and ice movements that were observed during each event

  - the type of support vessels and ice management activities at the time of each event
  - the loads that were experienced during each event

- to review information that is available regarding vessel movements in broken ice channels and from other ship operations in pack ice, and select events that provide quantitative information that is relevant to the question of loads on moored vessels in ice

- to extract relevant information for each event, including:

  - the details of each vessel such as name, class and characteristics and where relevant, escort or support vessel details
  - the time of each event, and the ice conditions that were observed during each event
  - relevant "load data" for each event (eg: vessel power, speed and resistance)

- to assess the full scale load data obtained from moored vessels and ship transits in broken ice, and summarize it in combined scatter plots that tie the data together in the context of expected load levels on moored vessels in pack ice

- to extract relevant load data from a companion project (Comfort et al, 1999) that deals with moored vessel model test results, and compare it with the full scale data

- to give some guidelines and examples regarding the use of the full scale data set and its results, to estimate load levels on moored vessels in different Grand Banks pack ice conditions

1.3 Approach

The majority of the effort in this study has been directed towards identifying and extracting full scale load data that is relevant to the question of moored vessel stationkeeping in pack ice, and developing a data set with this information. The main focus of the data extraction work was placed on the information that was acquired in conjunction with drilling operations from the Kulluk, in the Beaufort Sea. This is the only moored vessel, on a world wide basis, that has stationkept in a "near full range" of moving pack ice conditions and represents an unparalleled source of relevant full scale experience. In addition, the Kulluk was routinely operated with a number of sophisticated real time monitoring systems to enhance the safety, efficiency and prudence of its operations. These systems provided a tremendous amount of well documented information about the pack ice conditions encountered during the vessel's operations, the mooring loads and vessel response motions that were experienced, and the effects of different types of ice management support. Although some of this information has been lost over the course of time, a considerable portion of it has been maintained in various reports and files. This is fortunate, because the Kulluk information is a unique and valuable data set, which forms the primary basis for this work.

Efforts were also made to obtain relevant full scale information from other sources, such as Canmar's drillship operations and "more general ship operations" in ice. Although Canmar did gain a great deal of in-ice operating experience with their Beaufort drillship fleet, there was very little documentation around their operations, particularly with regard to the loading levels experienced by these moored vessels. As a result, there is basically no quantitative information from Canmar's drillships that is either available, or can be meaningfully used in this study. This is unfortunate but perhaps not too consequential, because these drillships usually worked in open water or light ice conditions, and tended to avoid difficult pack ice situations when they arose. With regard to full scale information from ship operations and performance trials in ice, some quantitative data has been identified that has analogies with the question of pack ice loads on moored vessels. However, the number of relevant "load events" from this full scale ship data source is limited, and have simply been compared with "equivalent Kulluk information" to ensure that they logically fit in. Notwithstanding these comments, the blend of information that has been provided in the full scale data set is considered to be of significant value.

As a secondary part of the study, the data set has also be exercised to identify key trends that are indicated by the full scale load information. Because of limitations in the scope of work, this assessment is not "all embracing". However, it is sufficiently thorough to highlight the most important implications of the full scale data, to a reasonable level.

Comparisons between the full scale data set and the results of various model test programs on moored vessels in moving ice have also been made in this study, in a fairly cursory manner. Again, the intent of these intercomparisons is simply to ensure that these "data sources" can be reasonably tied together, and show some degree of compatibility.

As a final stage to this study, the data set that has been developed was used to estimate expected load levels on moored vessels in moving Grand Banks pack ice conditions. This "data set application" has been carried out within the context of the following scenarios, to provide an example of how the data set can be used, and to present some representative information for floating systems in the Grand Banks region.

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

The information that is given in this report, and in the full scale data set that accompanies it, is seen as being both unique and highly meaningful. It is a very important source of "real world data", not only for future development activities in the Grand Banks area, but also for other regions of the world where moored vessel stationkeeping operations in moving pack ice are being considered.

2.0 Full Scale Experience

2.1 General

In this section of the report, some of the full scale experiences that have been gained with moored vessels in pack ice conditions are briefly highlighted. Although this information duplicates some of the discussion that was given in an earlier PERD report (Wright et al, 1998), it has been included to provide background, and for the sake of completeness. The main focus of this section is on the moored drilling vessels that have been used in the Beaufort Sea, since there is little other relevant experience, world wide. As noted earlier, the full scale data that has come from Beaufort Sea operations is unique, and forms the primary basis for this work.

Here, it is important to note that actual FPSO and offshore tanker loading operations have not yet been carried out in moving pack ice anywhere in the world. However, over the past few years, a considerable amount of effort has been directed towards this problem area, for potential developments on the Grand Banks and in other ice infested regions such as the northern Barents Sea, the Pechora Sea and the offshore Sakhalin area.

2.2 Beaufort Sea Systems

From the mid 1970's to the early 1990's, ice reinforced drillships and a conical drilling unit, named the "Kulluk", were used for exploratory drilling in the intermediate to deeper waters of the Beaufort Sea (20m - 80m). The first drilling operations were undertaken with Canmar's drillships, which were primarily intended for open water use, and normally operated during the Beaufort Sea's summer and early fall seasons. However, with icebreaker support, these drillships soon developed the capability to stationkeep in a variety of ice conditions. This extended their open water operating season, although they did not work extensively in heavy ice. By contrast, 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 typically operated in a much wider and more difficult range of ice conditions than Canmar's drillships.

The experiences that were gained with both types of drilling systems are relevant to the use of moored vessels in ice, particularly in terms of the design and operational progressions that were seen, the ice management approaches used, and the limitations that can be associated with each system. Here, the key features and operating histories of these floating drilling systems are highlighted. Since the Kulluk performed in a much more complete range of ice conditions than drillships, its experience provides the best analogy for vessel stationkeeping operations in various pack ice conditions and is dealt with in more detail. Before starting, there are two factors that are very important to recognize.

- the allowable offsets that were associated with the operation of these Beaufort drilling systems are much tighter than for an FPSO or a tanker loading operation. For example, when they were drilling, these Beaufort Sea vessels had to maintain position on their mooring systems with offsets not exceeding 5% of water depth. In 30m to 60m of water (where most of the drilling was carried out), this equates to maximum vessel excursions of 1.5m to 3.0m. Moored vessels that are stationkeeping on the Grand Banks in water depths of 80m to 200m, or in other deeper water regions, will have allowable excursions that are ten to fifteen times as great (15m to 45m).

- although the drillship and Kulluk systems did not work through the winter period, the ice conditions encountered in the Beaufort's extended season environment were at least equivalent to, and usually more difficult than the pack ice conditions that are expected on the Grand Banks and in most other regions.

2.2.1 Drillships

System Features

Canmar's drillships were used for exploratory drilling operations in the mid to deeper water areas of the Beaufort Sea, from 1976 until the late 1980's. Although these vessels were ice strengthened (to Baltic Class 1A Super levels) for seasonal operations in the Arctic offshore, they were relatively conventional drillships with displacements of about 15,000 tonnes and overall dimensions of roughly 100m x 20m x 9m (Figure 2.1). Each vessel was deployed with an eight point mooring system comprised of 2 3/4 " wire lines (four bow and four aft) that came off the deck and through the waterline (except for the Explorer 4 which had underwater fairleads). These mooring lines were equipped with remote anchor releases (RARs) that allowed the drillships to quickly disconnect from their anchors and move off location, should difficult ice or storm conditions occur.

Figure 2.1 Canmar's drillships were used for exploratory drilling operations in the Beaufort Sea from 1976 until the late 1980's. Although these vessels were ice strengthened for operations in the Arctic offshore, they were relatively conventional drillships with fairly weak mooring systems (≈100 tonne capacity). Ice management support was quite effective in allowing them to stationkeep in various pack ice conditions. This photo shows the Explorer 4 drillship (which had underwater fairleads) operating in thin moving pack ice conditions during the late freeze-up period, with ice management support vessels working updrift of the drillship. The ice management technique that was being used at the time involved a "circular breaking" pattern.

The drillship mooring systems were not designed to be particularly capable in ice, but could resist global ice forces of about 100 tonnes (an order of magnitude less than a typical FPSO) with acceptable vessel offsets and tensions in the individual lines. However, once moored, the drillships were aligned in a fixed direction and could not reposition themselves in response to changing ice drift directions without moving. From an ice management perspective, typical support for drillship operations consisted of one or two CAC 4 supply vessels and at times, the Robert Lemeur (CAC 3) and/or the more highly powered Kigoriak (CAC 2) icebreakers.

Operating Experience

Over the course of the past twenty years, these drillships have gained a considerable amount of operating experience in the Arctic offshore, conducting drilling operations at more than 40 locations in the Beaufort and Chukchi Seas. The majority of these wells were scheduled for the summer and fall periods when open water and relative light ice conditions are common, with a view to avoiding heavy ice. However, due to the nature of the Beaufort's environment, Canmar's drillships were often exposed to difficult ice conditions and as a result, developed ice management and alert procedures that enabled fairly efficient stationkeeping in certain ice situations.

The drillship performance capabilities that have been established on the basis of this in-ice operating experience are summarized in Table 2.1. This table also highlights the ice conditions encountered and the ice management support levels employed. In isolation, it is clear that the stationkeeping capability of these drillships was limited by the strength of their mooring system, and the fact that they could only orient their bow into the direction of expected ice action and not vane in response to short term changes in ice drift direction. However, with ice management support, these drillships often worked through moderate to relatively high ice concentration conditions that involved frequent changes in ice drift direction, provided the ice was managed into small pieces and could flow around them.

Table 2.1 Drillship performance capabilities in moving pack ice conditions.

Season & Representative Ice Conditions	Typical Level of Ice Management Support	Performance Capability & Typical Downtime Levels
Late Break-up & Summer Season		
Low to moderate concentrations of moving first year ice floes 1m to 1.5m thick, and hundreds of metres to several km in size	2 CAC 4 support vessels and 1 CAC 2 icebreaker, as required	Good stationkeeping capabilities. Typically low levels of downtime with several interruptions per month, lasting anywhere from less than a day to several days, and increasing with increasing ice concentration and drift speed.
Low to moderate concentrations of thin small first year ice floes from 0.3m to 0.7m thick, and tens to several hundred metres in size	2 CAC 4 support vessels	Good stationkeeping capabilities. Low to no downtime levels.
High concentrations of thick first year ice with several tenths multi-year ice in the pack, with large floes several km in size	3 CAC 4 support vessels and 1 CAC 2 icebreaker	Limited stationkeeping capability. Significant and lengthy downtime occurrences.
Freeze-up Season		
Low to moderate concentrations of thin moving ice, a few tens of cm thick with floes hundreds of metres to several km in size	2 CAC 4 support vessels	Good stationkeeping capabilities. Low to no downtime.
Thin continuous first year pack ice to 30 - 50 cm thick, moving along the drillship's axis	2 CAC 4 support vessels and 1 CAC 2 icebreaker, as required	Low downtime levels, with interruptions limited to periods of high speed ice movement (0.4 m/sec or more)
Thin continuous first year pack ice to 30 - 50 cm thick, moving towards the drillship's axis	2 CAC 4 support vessels and 1 CAC 2 icebreaker, as required	Moderate to high levels of downtime, with stationkeeping limited by the high ice forces associated with rubble build-up

Learnings and Limitations

The following comments are intended to summarize the experience that was developed on the basis of drillship stationkeeping operations in ice. Most of the factors that are identified were recognized in the design of the second generation Kulluk system, and are also relevant to the design and operation of any moored vessel system that is intended for use in moving pack ice conditions on the Grand Banks, or elsewhere.

- fairly conventional drillships maintained location on relatively weak mooring systems in a wide range of pack ice conditions, within tight offset tolerances and with reasonable levels of stationkeeping efficiency.

- ice management support had a very significant effect in providing drillships with the ability to stationkeep in ice.

- ice monitoring, ice management and ice alert procedures were developed to enhance the safety and efficiency of drillship operations in ice, and were quite successful in this regard.

- the fact that drillships had essentially no capability to break ice on their own has had little impact on their stationkeeping performance, since the ice management support vessels carried out all of the icebreaking that was required.

- the fact that the orientation of the drillships was fixed is a significant consideration, since relatively low forces were typical when broken ice moved against their bow or stern, but higher ice force levels were experienced when ice moved against their longsides and did not clear.

- the relatively weak drillship moorings were generally not capable of resisting the forces caused by high concentrations of thick moving ice or the impacts from significantly sized floes (hundred of metres), within acceptable tension and offset tolerances.

- the fact that the drillship mooring lines came off the deck and through the waterline was often a problem, because they were exposed to moving ice which tended to hang up on them, impeding ice clearance and increasing line tensions.

- the manner in which the ice cleared around the drillships and their mooring lines was very important, since good ice clearance tended to result in low ice forces and poor clearance (with the build-up of ice rubble) tended to result in unacceptably high forces (greater than their 100 tonnes mooring system capacity). Onboard bubblers on the Explorer 4 drillship enhanced ice clearance around the vessel during late season drilling operations.

- during the summer period, the drillships were usually quite effective in low to moderate concentrations of ice floes of any thickness that could be managed, while in freeze-up conditions, operations could proceed in thin moving ice, providing it cleared around the vessel.

- damage to the drillship hulls because of high local ice loads was not of concern and was never experienced in managed first or multi-year ice conditions, even though they were only strengthened to Baltic Class 1A Super standards.

- in terms of the ice conditions that limited drillship stationkeeping operations, the most difficult situations for these vessels, their moorings, and their ice management systems involved:

    - large rough ice floes that could not be managed, regardless of the ice concentration levels (eg: rubble fields, multi-year floes).

    - moderate to high ice concentrations of medium to thick first year ice, particularly when the pack ice cover was moving at relatively high drift rates.

    - thin ice movements perpendicular to their long axis during freeze-up, which resulted in a build-up of rubble due to poor ice clearance, and a rapid increase in load levels on their mooring system.

2.2.2 The Kulluk

System Features

The Kulluk's design recognized some of the shortcomings of drillship operations in ice, and incorporated a variety of features to improve the vessel's performance capability over a more demanding range of ice conditions. For example, the following key technical challenges were considered and accommodated in the Kulluk system's design.

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

- providing a strong mooring system that could resist the higher ice force levels associated with heavy ice conditions during extended season operations, with acceptable line tensions and vessel offsets.

- developing a submerged mooring system that would eliminate the problems that drillships experienced with ice entanglement at the waterline.developing a hull form that would 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.

- configuring an ice management system that would be capable of dealing with the more difficult ice conditions expected in the Beaufort's extended drilling season.

The Kulluk's key design features are shown in Figure 2.2. In terms of dimensions, the vessel had deck and waterline diameters of 100m 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 that, in combination with its circular shape, provided an omnidirectional capability to resist ice and storm forces. The mooring system was comprised of twelve 3 ½ inch wire lines and was capable of resisting relatively high ice forces. As was the case with the drillships, these lines were 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 very good icebreaking and ice clearance capabilities, which reduced the ice force levels and minimized the tensions that were experienced in the mooring lines, along with the vessel's response motions in ice. Since the vessel had no propulsion, it was basically a large conical barge that had to be towed when moving from one location to another. Again, ice management was a very important factor in enhancing the Kulluk's stationkeeping performance in ice, as well as in towing the vessel. Typically, the Kulluk was supported by between two and four CAC 2 icebreakers during its Beaufort Sea operations in heavy pack ice conditions (Figure 2.3)

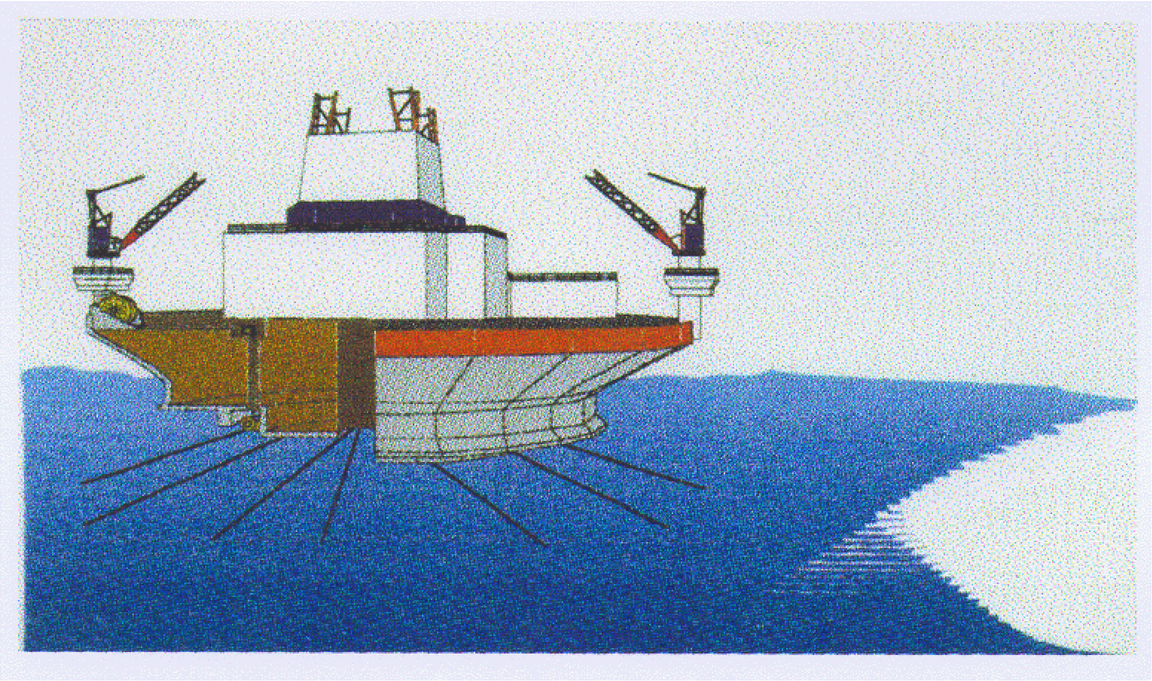

Figure 2.2 A schematic illustration of the Kulluk showing its key design features.

Figure 2.3 CAC 2 icebreakers provided very effective ice management support for the Kulluk drilling vessel. This photo shows two of Beaudril's CAC 2 support icebreakers, the Terry Fox (24,000 HP) and the Ikaluk (14,800 HP)

Operating Experience

After it entered the Beaufort Sea in 1983, the Kulluk drilled twelve wells at seven different locations, 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, with activities usually being suspended because of relief well drilling restrictions, rather than limitations in the stationkeeping capabilities of the Kulluk system itself. During these drilling operations, the vessel was exposed to a wide range of pack ice conditions and, with good ice management support, performed extremely well. As was the case with the Canmar drillships, environmental monitoring, ice management and ice alert procedures were a very important contributor 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 operating capabilities of the Kulluk have been well established from both design and operational experiences over a wide range of 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, large pressure ridges, heavy rubble and/or significant concentrations of multi-year ice were present in the moving pack ice cover. The 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 2.4 to 2.6 show representative examples of Kulluk stationkeeping operations in these types of pack ice situations. Although the Kulluk often operated in severe ice conditions, the amount of downtime that was incurred was very low. For example, during its first six operating seasons in the Beaufort Sea (1983 to 1989), the Kulluk experienced 44.7 down days and 8 moves off location in a total of 585 operating days, for an operating efficiency of about 92%. These ice downtime events were the result of “red and black alerts” which were called within the scope of the Kulluk's ice alert system, that was designed to ensure prudent operations. Again, it is important to recognize that the Kulluk’s offset tolerances relative to the wellhead were limited to several metres during its stationkeeping operations. In heavy ice conditions, individual mooring line tensions had the potential to increase quite rapidly as ice loads built-up, due to the relative stiffness of the Kulluk’s mooring system.

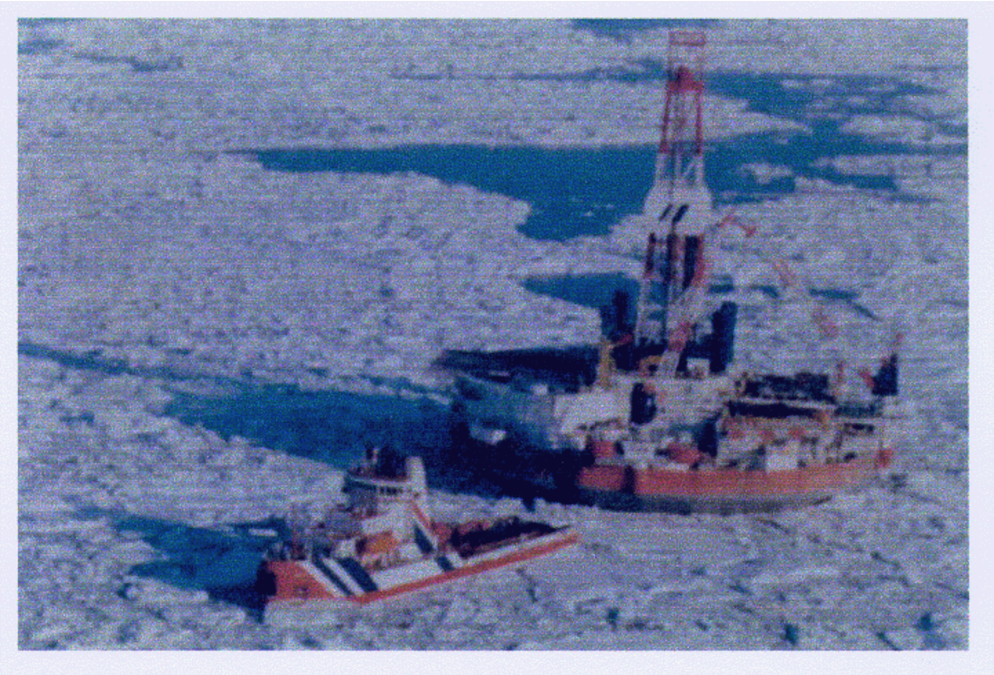

Figure 2.4 **The Kulluk often drilled in very difficult pack ice conditions. This photo shows the Kulluk stationkeeping in thick managed first year ice during a summer ice intrusion.**

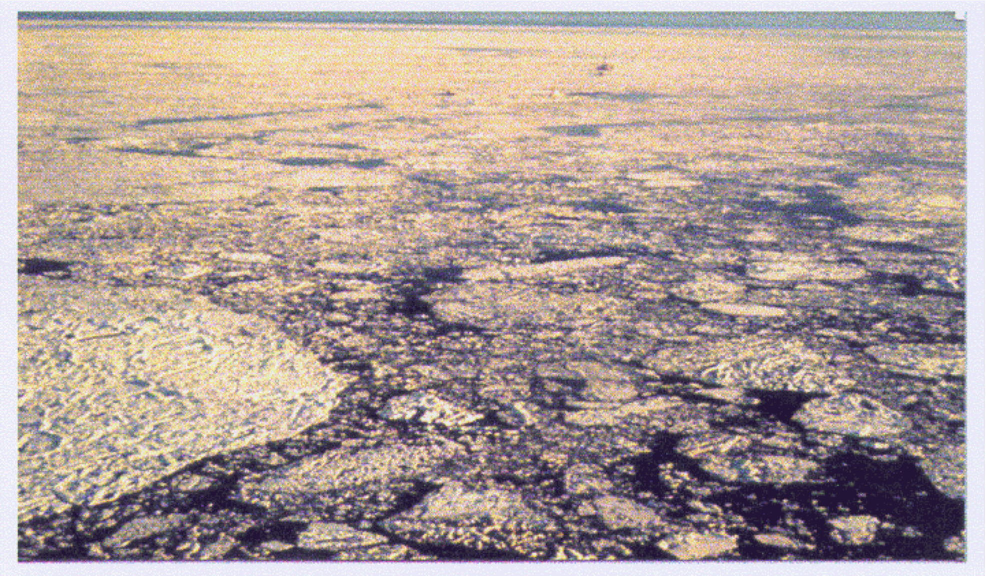

Figure 2.5 **This photo shows updrift ice management while the Kulluk was drilling in moving first and second year pack ice conditions, with rough "stamukha" features from hundreds of metres to several kilometres in extent. A "picket boat" ice management strategy was usually used in these types of situations.**

Figure 2.6 **This photo shows the Kulluk stationkeeping in late freeze-up/early winder pack ice conditions, with two vessels managing the oncoming ice cover updrift. The ice management technique that was being used at the time involved tandem linear tracks through the oncoming ice cover. The pack ice was near continuous in terms of its concentration, was about 1m in thickness, and had frequent areas of ridging and rubble within it. During the late freeze-up and early winter period, poor visibility conditions caused by frequent occurrences of fog and the long polar darkness, were often an impediment to operations, but were successfully dealt with.**

Since ice and performance monitoring programs were used to provide real time support for the Kulluk's stationkeeping operations, an extensive data set was gathered on the mooring loads and motions that the vessel experienced in different ice conditions, together with the nature of the ice interactions and the effectiveness of the ice management techniques that were used. This information is very relevant to the question of moored vessel stationkeeping in moving pack ice conditions and as mentioned earlier, forms the primary basis for this study work.

The Kulluk's mooring system was originally designed to withstand the loads from 1.2m of level unbroken ice, when the vessel was operating in a stationkeeping mode with no ice management support. Given the ideal mooring line lengths, orientations, pretensions and anchor holding capacities that were assumed during its development, the Kulluk's mooring system was nominally designed to tolerate:

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

- global loads in excess of 1000 tonnes in a survival mode, when the riser was disconnected, 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), which resulted in a typical mooring system capability in the range of 400 - 500 tonnes in a drilling mode, and 800-1000 tonnes in a survival mode. Ice interaction events that were expected to cause mooring loads in excess of these levels would trigger an ice alert sequence that could culminate in a move off location, through the Kulluk's alert procedure. It should be noted that this mooring system capacity was far in excess of that of Canmar's drillships, but is low in comparison the types of mooring systems that are being considered for the Grand Banks, and for other ice infested areas of the world.

Although the Kulluk occasionally operated in unbroken ice conditions, the vessel normally worked in managed ice, where the oncoming 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 rare in moving Beaufort Sea pack ice. As a result, ongoing ice management was usually required to fragment the ridges, rough areas and thicker old floes that were commonly interspersed throughout the ice cover, to keep anticipated mooring load levels and vessel offsets within acceptable limits.

2.3 Other Vessels

In addition to the experiences that have been gained with Beaufort Sea drilling vessels, there are a variety of other full scale marine operations which have potential to provide some useful insights into the question of moored vessel stationkeeping in moving pack ice conditions. These operations involve the opposite process of a self-propelled vessel moving through the ice, and towed movements of ships and other structures through near-stationary broken ice conditions. The two processes are not strictly exact reflections of each other, in that a moored vessel generally experiences a mooring load response that varies with its lateral displacement and a dynamic response as part of a mass/spring system. A self-propelled or towed vessel, on the other hand, operates under a fairly constant propelling force. However, at slow steady speeds of advance that are consistent with typical pack ice drift speeds, the average ice force on (or ice resistance of) a self-propelled or towed vessel should be virtually identical to the load on the same vessel, moored in the same ice, drifting at the same slow speed.

Ship operations have been routinely carried out in a wide range of ice conditions for many decades. Here, there is no need to review the full scale experiences that have been gained with vessels in ice, since they are quite commonly known. However, it is considered worthwhile to make the following basic but important points.

- it is well known that the ice resistance on a vessel moving through unbroken ice is much higher than in broken ice conditions. In principle, this is analogous to the load reductions seen on moored vessels in managed ice, and supports some of the general comments that have already been made about the benefits of ice management support.

- icebreaker escorts of less capable ships is common marine practice, and a prime example of the significant load (or resistance) reductions that can be experienced by vessels in prebroken and often looser ice conditions. The thrust of many of the less capable ships that are escorted in ice is often limited to something in the order of tens of tonnes to a hundred or so tonnes, which gives some indication of mean load levels on typical vessels in broken ice conditions.

- the large structure tows (eg: Molikpaq, SSDC) that have been successfully carried out on a number of occasions offer another example. In these cases, tow vessels with bollard pulls in the range of two hundred tonnes have effectively moved large structures through prebroken ice. Again, this type of experience gives some indication of mean load levels.

- to counterbalance these points, there is also experience with ships being stopped by rough ice and pressure, higher resistances when turning, and broken towing and mooring lines.

Most types of ship operations in ice can provide relevant insights into the question of loads on moored vessels, although many of these insights are not quantitative in nature. A listing of the vessel operations that have been considered for the purposes of this work includes.

- dedicated ship trials in broken ice conditions, or in broken ice channels, which are usually carried out for most newly built icebreakers
- documented and instrumented ship voyages in ice, such as the Arctic Ocean Transect of the Louis St. Laurent and the Polar Sea in 1994
- delivery and relocation tows of barges and structures involving some ice transit, such as the tows of the SSDC, Kulluk and Molikpaq into and within the Beaufort Sea
- various ship "operating events" like those contained in a recent Arctic Tanker Loading Study (Canmar et al, 1995), where some relevant documentation and recollections were used to estimate load levels in different ice situations

Although all these types of vessel operations have been considered, only a few have produced quantitative information about ice loads in pack ice conditions that can be readily used here.

3.0 Full Scale Data Sources

3.1 General

In this section of the report, the full scale data sources that have come from experiences with moored vessels and other ship operations in pack ice are briefly highlighted. The intent of this section is to provide the reader with some feel for the type of information that is available, and to more specifically outline what has been used as a basis for this work. Here, only Kulluk and "other in-ice ship operations" data sources are described. Unfortunately, there is virtually no quantitative information that was either collected or remains about the loads experienced by Canmar's drillships.

3.2 Kulluk

The primary source of full scale data on moored vessel stationkeeping operations in moving pack ice conditions comes from the Kulluk's experience in the Beaufort Sea, as noted earlier. The level of information that was obtained during Kulluk operations was comprehensive, in comparison to any other full scale data source. This information also provided a high level of detail about key factors, and was documented on a systematic basis. The range of Kulluk data that was acquired is highlighted as follows:

Mooring System

- the "characteristics of the Kulluk vessel" were essentially the same during all of its in-ice stationkeeping operations, but the manner in which its mooring system was deployed and the capability of its mooring system, varied from location to location

- specific details about the Kulluk's "as deployed" mooring system were well documented for each one of its deployment, including:

    - the number of mooring lines deployed
    - the length and orientation of each mooring line
    - the anchor(s) used on each mooring line
    - the pretension in each mooring line

- an example of the type of documentation that is available for the Kulluk's mooring system at each of its drilling locations is shown in Figure 3.1

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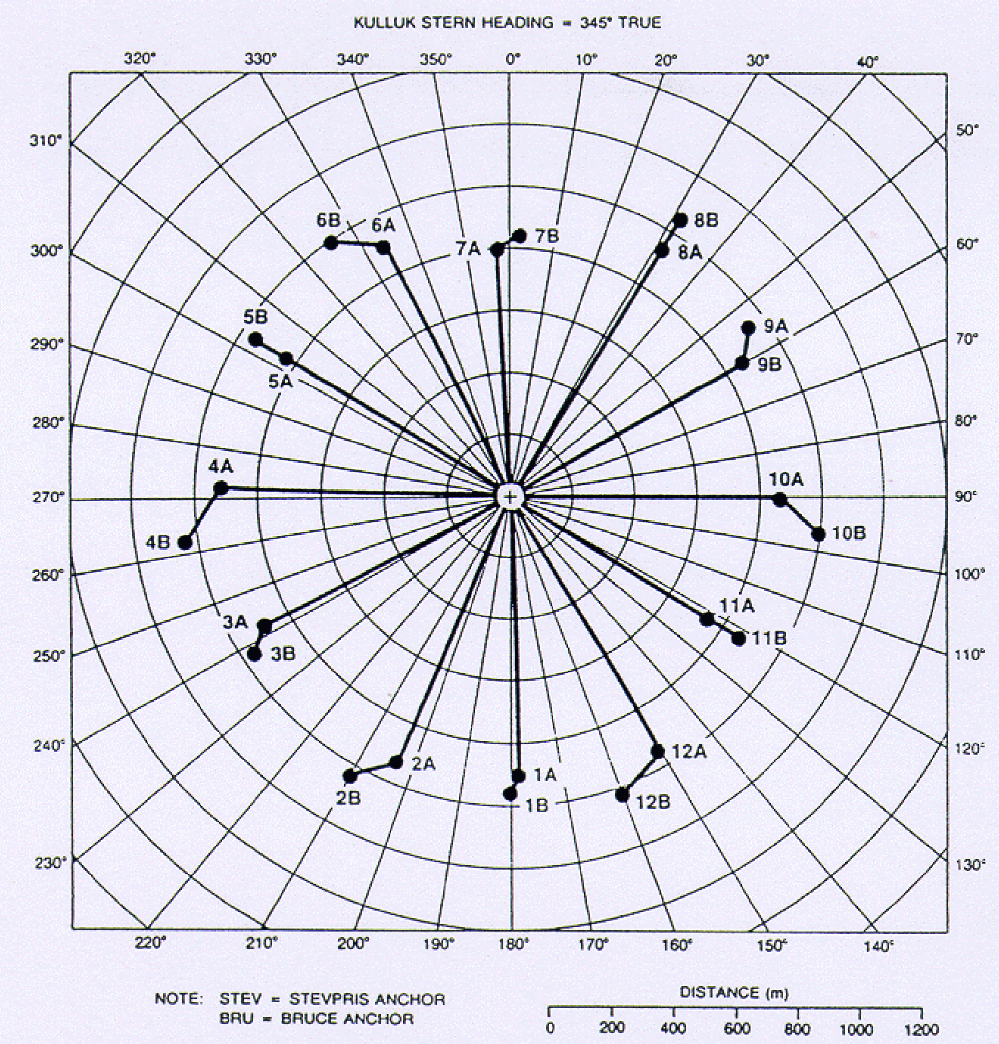
- it should be noted that mooring analyses were also run in “near real time” onboard the Kulluk once the mooring lines had been deployed and pretensioned, to establish the capacity of the mooring system to resist loads from different directions, as a quantitative guide during Kulluk stationkeeping operations

- as outlined in the next section, a description of the Kulluk’s mooring system is contained in the full scale data set, for each location where load event information is given



#	TYPE	DISTANCE (m)	BEARING (°T)	#	TYPE	DISTANCE (m)	BEARING (°T)
1A	15T STEV	905	179	7A	15T STEV	806	358
1B	9T BRU	945	180	7B	9T BRU	848	001
2A	15T BRU	945	204	8A	15T BRU	940	031
2B	12T BRU	1029	210	8B	12T BRU	1046	031
3A	15T STEV	886	241	9A	15T STEV	854	060
3B	9T BRU	957	239	9B	9T BRU	973	054
4A	15T STEV	924	272	10A	15T BRU	887	090
4B	9T BRU	1010	262	10B	12T BRU	999	097
5A	15T STEV	821	303	11A	15T STEV	751	121
5B	12T BRU	957	303	11B	9T BRU	991	122
6A	15T STEV	913	332	12A	12T BRU	925	150
6B	12T BRU	995	326	12B	12T BRU	1002	155

KULLUK'S MOORING PATTERN AT AKPAK P-35
(09 JUNE TO 17 JUNE)

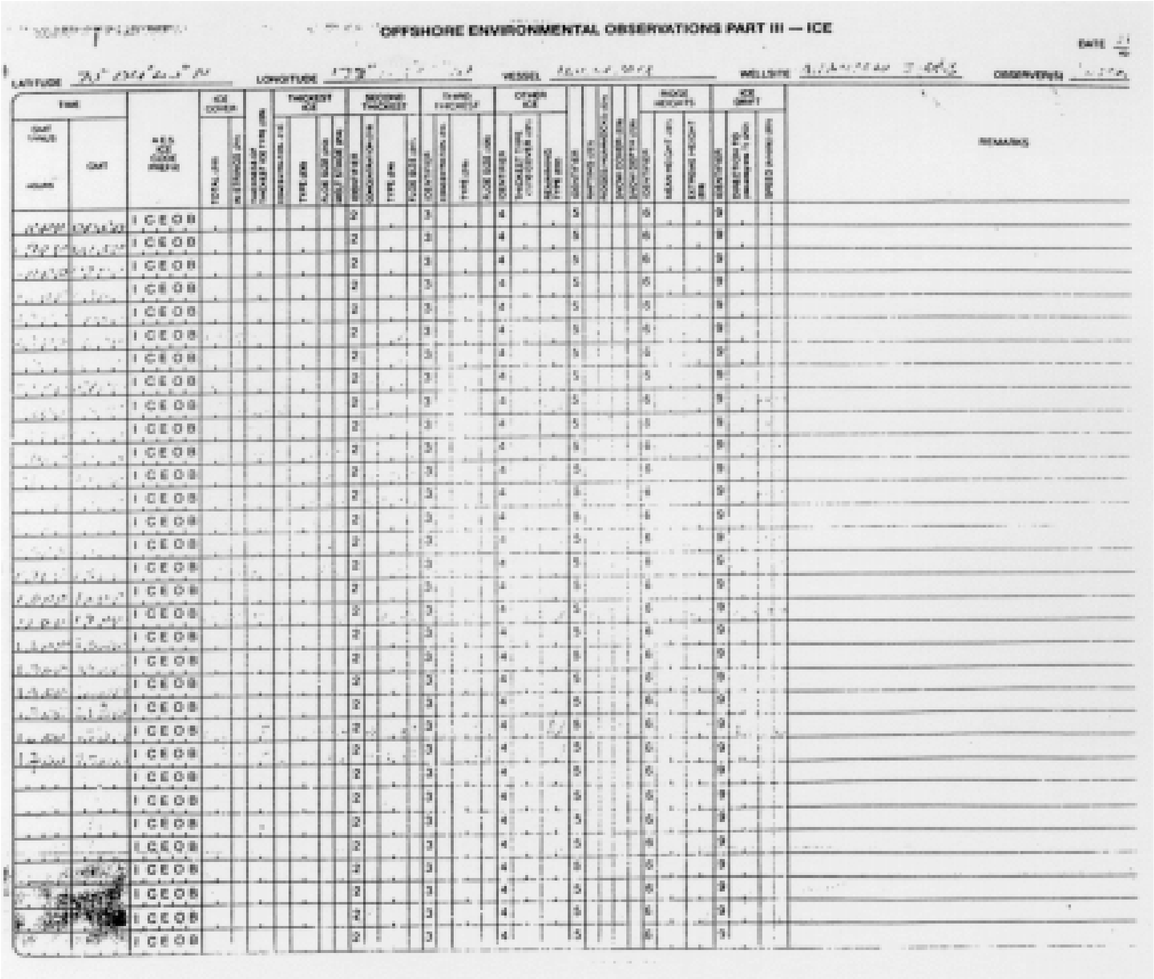
Figure 3.1 A representative example of the type of documentation that is available about the Kulluk's mooring system characteristics at each deployment site.

Ambient Ice Conditions

- details about the ice conditions that were present in the general vicinity of the Kulluk during stationkeeping operations (ie: the "far field conditions" prior to ice management) were documented by onboard environmental observers on an hourly basis, including:
    - ice concentrations
    - ice thicknesses
    - floe sizes
    - ridge frequencies and heights
    - ice drift speeds and directions

- these ice observations were visual estimates (made in accordance with the WMO and MANICE guidelines), with the exception of ice drift speeds and directions, which were obtained from sequential radar fixes on specific ice features

- an example of the type of "ice information log" that was filled out on an hourly basis, and provided some of the "ice conditions input" to the full scale data set, is shown in Figure 3.2 (similar weather and sea state logs were also routinely filled out by the observers)



OFFSHORE ENVIRONMENTAL OBSERVATIONS PART III — ICE

DATE

LATITUDE LONGITUDE VESSEL WELLSITE OBSERVER(S)

REMARKS

Figure 3.2 An example of the type of "ice conditions" observation form that was filled out on the Kulluk on an hourly basis.

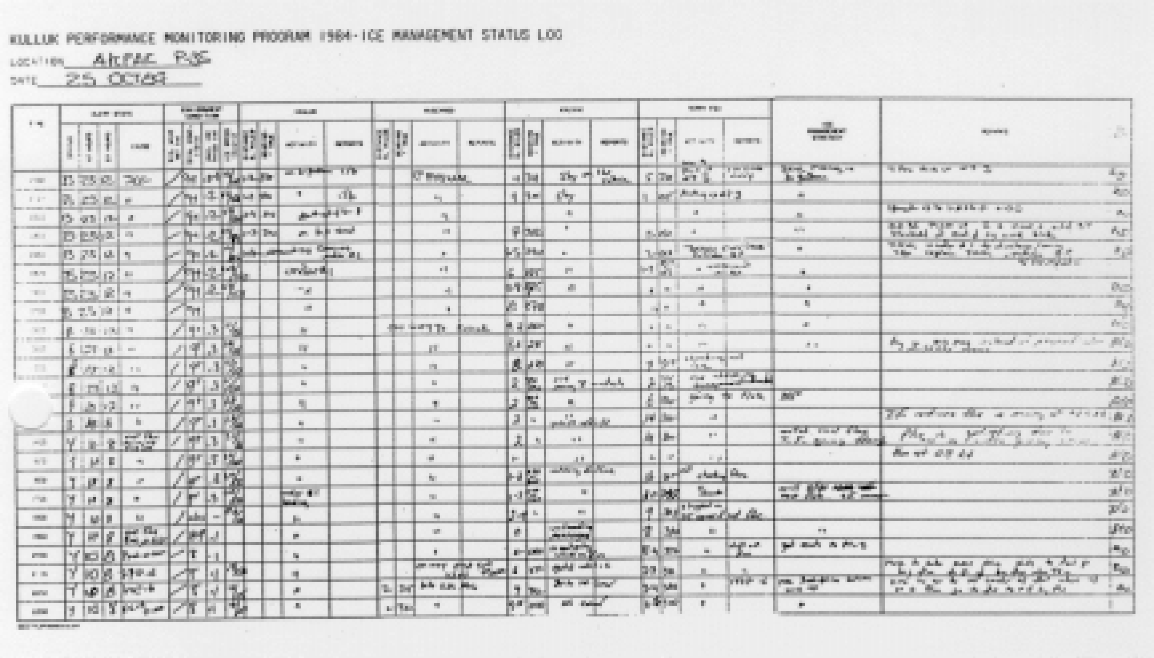
Ice Management

- details about the ice management vessels used and the type of ice management techniques employed were frequently noted by "ice advisors" (who provided functional onboard services as an integral part of the Kulluk's marine crew)

- this information was not always documented as systematically as one might like, but did provide a good feel for ice management activities being carried out at most times, and for the effectiveness of these activities

- examples of the type of information that was often available are shown in Figures 3.3 and 3.4, with the first figure showing the type of "ice management log" that was sometimes kept, and the second giving an example the type of "real time ice management strategies" that were routinely developed and communicated to the support icebreakers to implement (ice areas were colour coded in accordance with the Kulluk's alert system)

- this type of information, along with notes about the managed ice conditions and types of ice interactions seen at the Kulluk, were also used to provide input to the data set

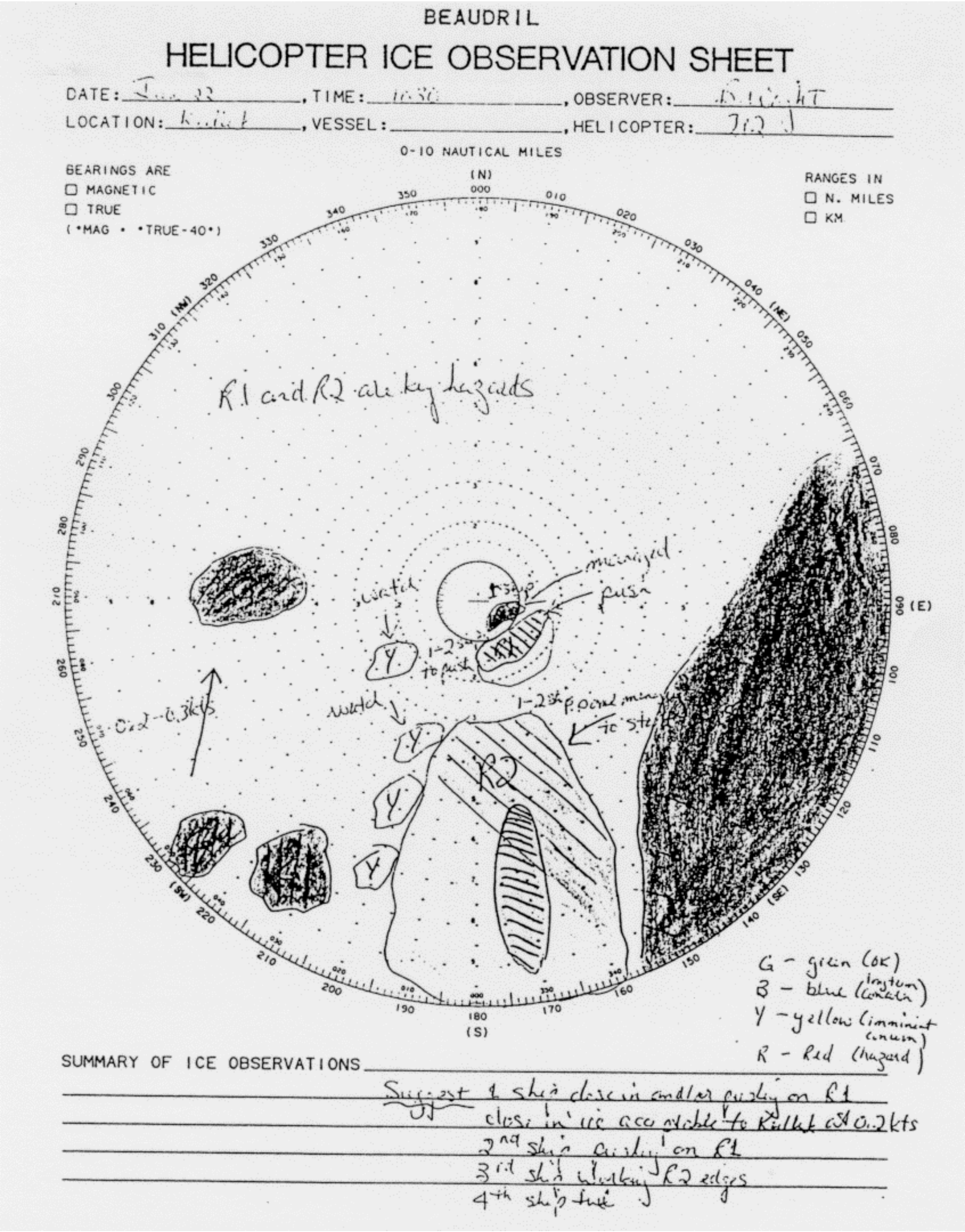


KULLUK PERFORMANCE MONITORING PROGRAM 1984-ICE MANAGEMENT STATUS LOG

LOCATION AKPAK P35

DATE 25 OCT 84

Figure 3.3 **An example of the type of "ice management log" that was routinely kept onboard the Kulluk.**



BEAUDRIL

HELICOPTER ICE OBSERVATION SHEET

DATE: [illegible], TIME: 1030, OBSERVER: Wright
LOCATION: Kulluk, VESSEL: ______, HELICOPTER: [illegible]

0-10 NAUTICAL MILES

BEARINGS ARE
☐ MAGNETIC
☐ TRUE
(•MAG • •TRUE-40•)

RANGES IN
☐ N. MILES
☐ KM

G - green (OK)
B - blue (longterm concern)
Y - yellow (imminent concern)
R - Red (hazard)

SUMMARY OF ICE OBSERVATIONS
Suggest 1 ship close in and/or pushing on R1
closing in ice accessible to Kulluk at 0.2kts
2nd ship pushing on R1
3rd ship working R2 edges
4th ship free

Figure 3.4 An example of the type of "ice management strategy" that was routinely developed onboard the Kulluk, and transmitted to the support icebreakers to implement in real time.

Loads & Responses

- a performance monitoring system was installed onboard the Kulluk that provided real time information on the tensions in its individual mooring lines, offsets from the wellhead, and the vessel's rotational (pitch, roll, yaw) and heave motions, at a frequency of 1 Hz

- this information, together with "global loads" that were vectorially calculated from the individual mooring line tensions, were displayed onboard in real time and recorded on magnetic tape for post analysis, with selected subsets of this information also continuously recorded on strip charts

- these data sources provided very detailed information about the magnitude and nature of the loads that the Kulluk experienced, along with the vessel motions that occurred in response to these loads

- representative examples of the type of global loading data that was obtained with the Kulluk's performance monitoring system are given later in the report, for example, in Figures 5.25, 5.26 and 5.27

- these figures contain segments of the original global load time series that were recorded on strip charts, and include annotations about the "ice situation" that was occurring at the time

- this type of detailed loading information, or the results that have been extracted from similar plots, has been used to develop the load component of the full scale data set

- since care was taken to calibrate the Kulluk's line tension measurements and to correct any baseline drifts that were seen, the global load measurements that were obtained on the Kulluk are considered to be accurate to ≈ 15%

The foregoing information has been given to provide some feel for the range of full scale data that was acquired during the Kulluk's stationkeeping operations in Beaufort Sea pack ice. Not all of the original data has been kept over time but surprising, a substantial portion of it is still available. This original Kulluk data, plus the relevant but somewhat less detailed "analysed information" that is contained in the following types of summary reports, has been used as the primary basis for the full scale data set developed in this work.

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
Daily Barge Reports	- operational reports that were produced on the Kulluk daily
Daily Drilling Reports	- operational reports that were produced on the Kulluk daily
Environmental Observation Reports	- end of season summary reports prepared for each Kulluk site & submitted to COGLA

For the purposes of this work, the full scale data that was acquired during the first six years of the Kulluk's operations, from 1983 to 1989, was used. In total, this time period covers 585 days of stationkeeping operations with the Kulluk, most of which were in moving pack ice conditions.

3.3 Ships in Ice

In order for information from ship trials and other ship operations in ice to be of direct value in the present study, the following is required.

- should take place in fairly small pack ice floes or in broken ice, at low speeds
- ice thickness, coverage and, to a lesser extent, properties should be documented
- accurate measurements should be available for resistance and speed determinations
- level of documentation should allow ice conditions and vessel loads to be married

Of all the ship trials and other ship operations that have been carried out in ice, there are only a few which actually satisfy these requirements. They include:

Icebreaker Performance Trials in Broken Channels

Most new build icebreakers undergo dedicated ice trials, and they usually include resistance-speed tests in newly broken channels. These types of trials are normally well instrumented and documented, so that the relationship between ship resistance and speed, in known broken ice conditions in a channel, can be determined. Satisfactory resistance determinations usually require shaft thrust measurements and a knowledge of thrust deduction, normally from model tests. In the case of ducted propellers, a knowledge of the thrust augment is also required, again from model tests, or from comparable data based upon prior experiences with similar installations.

These types of trials, however, often only cover the middle and high speed range of the vessel, whereas this study's interest is at relatively low speed. Of the twenty three world icebreakers (other than Russian vessels) for which trials have been conducted over the past twenty years, broken channel resistance data at slow speeds are available for only eight. These are:

- the Beaufort Sea icebreakers/supply vessels Kigoriak, Kalvik and Ikaluk
- the Canadian Coast Guard vessels Franklin (R-Class), Louis St. Laurent and Ann Harvey (Type 1100)
- the US Coast Guard vessel Katmai Bay
- the Finnish Coast Guard vessel Otso (and Kontio)

All of these icebreaking vessels have different sizes and shapes, with vessel displacements ranging from 600 tonnes to 14,000 tonnes. The ship trials that were carried out with them were also conducted in different ice conditions. These trials were conducted according to good standard practice and most, but not all, of the information that is required for complete analysis was recorded. Where needed data was not recorded, reasonable assumptions were made.

The resistance versus slow speed data from the broken channel tests for these icebreakers has been analysed and documented in a number of studies (Keinonen et al, 1989,1991,1996). These studies have been used as the data source for the ship trials information considered in this work. It should be borne in mind that these broken channel tests represent a specific broken ice situation where, although the broken ice is generally not under pressure, lateral clearing of the ice past the transiting vessel is somewhat restricted. Therefore, one might expect this data to be in the high load range, relative to ice thickness and concentration, when compared to the loads on moored vessels in "more widely broken ice".

Instrumented Arctic Voyages

Many significant Arctic voyages have been carried out, and to varying degrees documented, over the past twenty years. These have included two Oden voyages to the North Pole, and several summer and winter voyages by the M.V.Arctic, Kigoriak, Terry Fox and Kalvik. Although these vessels met ice conditions that are of interest and relevance to this study, the level of instrumentation and documentation was not sufficient to allow for an accurate determination of cause (ice conditions and speed) and effect (resistance).

Only two data sets would appear to offer this potential, those for the Arctic Ocean Transect of the Louis S. St. Laurent and the Polar Sea in 1994. These are particularly well documented voyages, from which the data has been analysed for hull ice loading, propeller ice loading, and trafficability relative to ice regimes. The data, which includes complete voyage video records, might be further analysed to provide information on resistance versus a wide variety of broken ice conditions. However, this type of analysis would require significant resources which are well beyond the scope of this study.

Delivery and Relocation Tows of Barges and Structures

Many important towing events have taken place in ice, especially into and within the Beaufort Sea. It is unfortunate that none of these towing operations were instrumented and recorded to a level that is sufficient to provide meaningful information for this study.

Ship Operating Events

In a recent Arctic Tanker Loading Study (Canmar et al, 1995), twenty two separate “in-ice vessel operating events” were identified and documented, and load estimates developed for each event. These events covered a wide range of situations that were met during Beaufort Sea operations. However, the only “clean events” treated in this Canmar study were based on Kulluk operations, where well defined ice conditions were known to have caused directly measured loads. All of the other events were less clearly defined, because:

- the load estimates for these events came from a number of different sources at the same time (eg: ice and hull interaction observations, propulsion levels, and mooring or tow line breakage information)

- the loads on vessels moored to (or stationkeeping by) a structure were usually influenced by “shielding from the oncoming ice”, caused by the presence of another vessel or the fixed structure

- the loads were not directly measured but rather, were estimated from information on mooring or tow line breakage, propulsion/thruster power, etc.

- since the events involved unplanned occurrences that were “accidental” in nature, they were “simply” recorded in log books or incident reports, and the level of documentation lacked the detail needed for thorough analysis

Strictly speaking, only the few Kulluk events that were dealt with in Canmar’s study satisfied the data requirements specified earlier (namely, good documentation of cause - ie: the ice conditions, and effect - ie: the associated loads). However, some of the other ship operating events that were contained in the JIP do represent full scale situations and estimated load levels and as such, have been included as a data source for further evaluation in this work. Although they may not be sufficiently well defined to be considered any more than rough load estimates, there is value in determining whether or not they fall within expected load ranges, relative to other higher quality full scale data. This is the approach that has been taken with the ship event data given in Canmar’s JIP report.

4.0 Full Scale Data Set

4.1 General

As outlined earlier, the major part of this work involved the development of a data set that contains full scale information on the loads that have been experienced by moored vessels in pack ice. However, some relevant data from vessel trials in broken ice and from other in-ice ship operations has also been included, since this type of information has equivalences to the loads that have been directly measured on moored vessels. In this section of the report, the manner in which the full scale data set was developed is highlighted, and examples of the type of information that it contains are provided.

Clearly, a considerable portion of the overall study effort was directed to a review of the full scale information that is available, and the identification and extraction of relevant event data. As noted earlier, the primary data sources that were used for the data set include the Kulluk information and a number of ship trials and "operating events". Unfortunately, quantitative information from Canmar's drillship operations is virtually non-existent, while other full scale data sources are simply not available.

One of the challenges in the work was to configure the data set in a way that would sensibly reflect "all of the key parameters" that are important to the question of loads on moored vessels in pack ice, then find this information for each event. Although this process was far from perfect and there are gaps in some of the information, the full scale data set that has been developed is quite comprehensive and in fact, quite remarkable. Another challenge was to include entries that would allow data from different sources (ie: from the Kulluk, from ship observations, and from physical model tests) to be intercompared. This was accomplished by devising a methodology that could be used to standardize information from different sources to a "common vessel form", and ensuring that all of the parameters that are required to apply this methodology were included in the data set. The development of the full scale data set and its contents are highlighted as follows.

4.2 Approach

When developing the full scale data set, the first step that was taken was to identify "all of the important factors" that should be reflected in it. Since the primary intent of the data set was to include relevant information from full scale observations on moored vessels like the Kulluk and Canmar's drillships, this "type of scenario" was used to set the scene.
Quite clearly, the most basic information that should be reflected in the data set includes:

- details about the location of the moored vessel's operation
- details about the characteristics of the moored vessel
- details about the characteristics of the vessel's mooring system
- details about the date and time of each ice loading event

In terms of specifying other relevant information for the full scale data set, the approach that was used was to identify all of the "key factors" that a moored vessel should be concerned with in a logical manner, from the perspective of "operations on its bridge". These factors and the logical thought progressions that are associated with them are illustrated in Figure 4.1. This logic framework has been used as a basis for specifying all of the "relevant parameters" in the data set. In general terms, the factors include:

- details about the ambient ice conditions updrift of the moored vessel's operation
- details about the ice management support that was provided
- details about the managed ice conditions and type of ice interactions that were seen at the moored vessel
- details about the magnitude and nature of the loads that were experienced

Specific entries for the full scale Kulluk information that is contained in the data set have been developed along these lines.

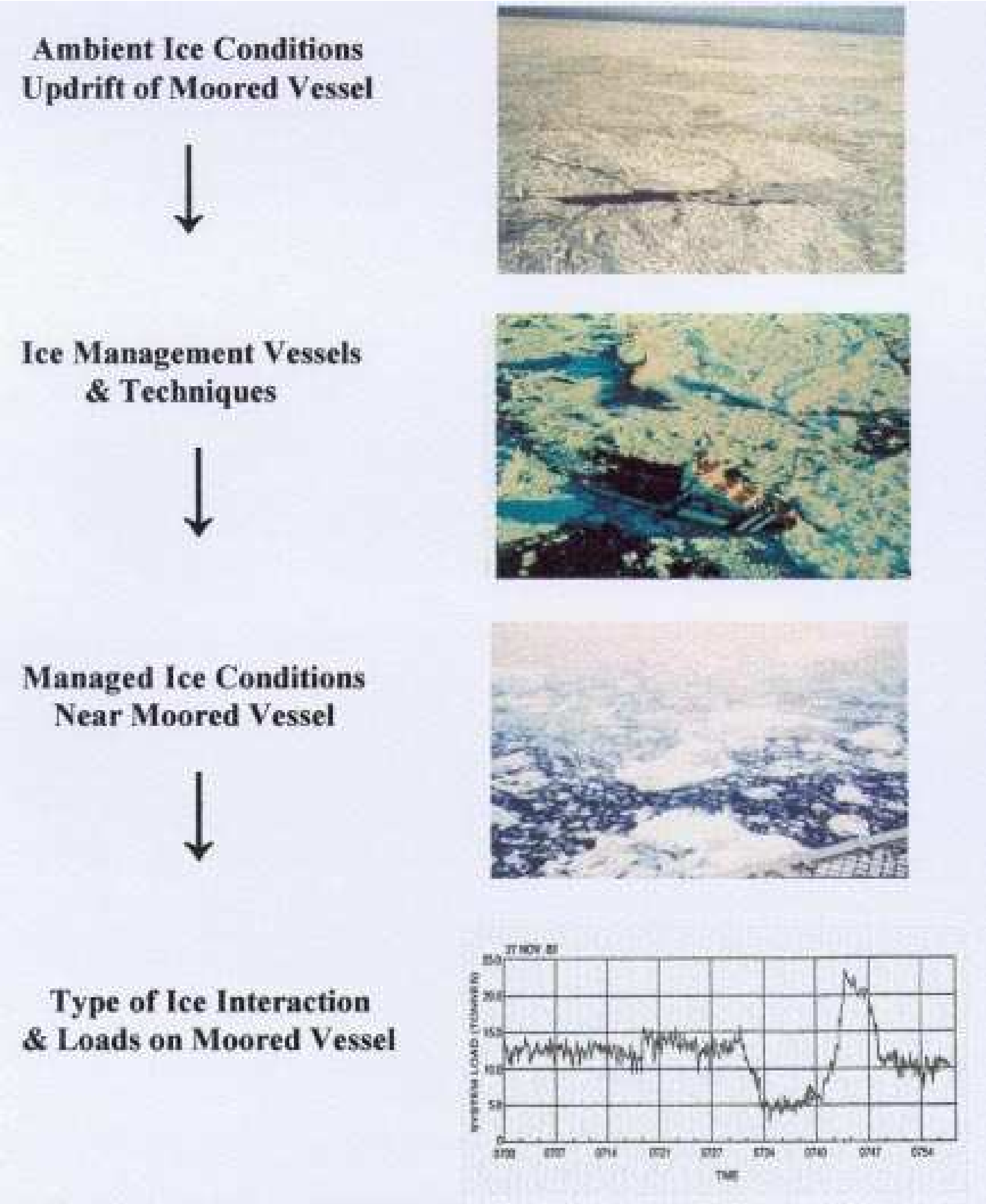


Figure 4.1 The basic logic framework that was used in the development of the full scale load data set.

The information that is available from ship trials and other in-ice ship operations is somewhat different and does not fit into this "logic framework" as easily. Despite this fact, the same basic categorizations have been used in the ship component of the data set, to allow for reasonable comparisons between different data sources. Where necessary, slight changes have been made in the specific ship data entries. For example:

- mooring system characteristics have been replaced by a brief description of the nature of the vessel's operation

- details about ice management support have been simplified (eg: vessel breaking ahead)

The full scale data set has been developed in Excel format, and is provided as a large Excel workbook that is comprised of a number of separate worksheets. The individual worksheets, which contain the major "segments of the data set", include:

- the full scale Kulluk event data
- the full scale ship trials and ship operations event data
- the specific characteristics of the Kulluk and other ships that are in the data set
- the specific characteristics of the Kulluk's mooring system at all of the "Kulluk event locations" that are in the data set

Details about the structure of the data set and the individual data entries that are contained in it are given as follows, along with some related comments.

4.3 Kulluk Data Entries

The specific data set entries that have been used in the Excel spreadsheet follow the "logic framework" that was outlined above in a very direct manner. Since the Kulluk data forms the major part of the full scale data set, the entries that are included in the "Kulluk worksheet" are highlighted first.

General Information

The first grouping of entries in the Kulluk worksheet provides basic information about the location of the vessel's operation when "ice events" were encountered, and the date and time of these events. The specific entries include:

- vessel name
- vessel characteristics
- mooring configuration
- location

- date of event
- time of event

In the columns that are titled vessel characteristics and mooring configuration, the user is referred to two other worksheets in the data set, in which detailed information about the "vessel characteristics" and mooring system at the specified location are given

An example of this portion of the worksheet is shown 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 Pitsiulak A-05 / 83 mooring description in mooring configuration sheet	Pitsiulak A-05	7-Sep-83	0130
Kulluk	see Kulluk description in vessel characteristics sheet	see Kulluk Pitsiulak A-05 / 83 mooring description in mooring configuration sheet	Pitsiulak A-05	7-Sep-83	0320
Kulluk	see Kulluk description in vessel characteristics sheet	see Kulluk Pitsiulak A-05 / 83 mooring description in mooring configuration sheet	Pitsiulak A-05	7-Sep-83	0400
Kulluk	see Kulluk description in vessel characteristics sheet	see Kulluk Pitsiulak A-05 / 83 mooring description in mooring configuration sheet	Pitsiulak A-05	7-Sep-83	0510

Ambient Ice Conditions

The second grouping of entries in the Kulluk worksheet deals with the ambient ice conditions that were seen in the general vicinity of the moored vessel during each specified load event. The intent of including this data is to give the user some feel for the type and severity of "far field' ice conditions that were present updrift of the Kulluk. This information is representative of the overall ice regime that the Kulluk "system", including its ice management support vessels, had to contend with. Specific entries include:

- total ice concentration	(visual estimate)
- ice concentration by type	(visual estimate)
- ice thickness by type	(visual estimate)
- typical floe size	(visual estimate)
- larger floe size	(visual estimate)
- ridging concentration	(visual estimate)
- typical ridge sail height	(visual estimate)
- typical ridge keel depth	(based on keel/sail ratio of ≈ 4.5)
- larger ridge sail height	(visual estimate)
- larger ridge keel depth	(/keel/sail ratio of ≈ 4.5 & any grounding reports)
- related comments	(any related points)

-	ice drift speed	(sequential radar fixes)
-	ice drift direction	(sequential radar fixes)
-	"state" of the ice cover	(eg: close, open, pressured ice)
-	flexural ice strength	(inferred from other parameters)

Most of these ice conditions entries are self explanatory and do not require further comment. However, it should be noted that ice properties and strengths were not measured during any of the Kulluk's operations and accordingly, ice strengths had to be estimated from other parameters, for each event. The approach that was used to approximate rough 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 being 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 on the other hand, should not be unreasonable.

An example of the type of "ambient ice conditions" entries that are contained in this portion of the Kulluk worksheet is given as follows.

Ambient Ice Conditions

Total Ice Concentration *(10ths)*	***Concentration by Type*** *(10ths)*	***Ice Thickness by Type*** *(m)*	***Typical Floe Size*** *(m)*	***Larger Floe Sizes*** *(m)*
9+	9+ - GW	0.15 - 0.3	500 - 2000	500 - 2000
4	4 - TFY	1.2	500 - 2000	2000 - 10000
7	6 - TFY 1 - SY	1.5 3.5	500 - 2000	2000 - 10000
3	3 - TFY	1.0	500 - 2000	2000 - 10000
8	8 - TFY	1.0	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***
4 - 6	1 - 2	5 - 10	4 - 5	20 - 25	some floebergs present in pack, from hundreds of m to several km in extent
4 - 6	1 - 2	5 - 10	4 - 5	20 - 25	some floebergs present in pack, from hundreds of m to several km in extent
6 - 8	2 - 3	10 - 15	6 - 7	30 - 35	some floebergs present in pack, from hundreds of m to several km in extent
3 - 4	2 - 3	10 - 15	4 - 5	20 - 25	some floebergs present in pack, from hundreds of m to several km in extent

Ice Drift Speed *(m/sec)*	***Ice Drift Direction*** *(degrees true)*	***"State" of the Ice Cover***	***Flexural Ice Strength*** *(kPa)*
0.5	130	very close pack, with significant roughness	350
0.25	130	very close pack, with significant roughness	420
0.3	230	very close pack, with significant roughness under pressure	505

Other Factors

The third grouping of entries in the Kulluk full scale data worksheet deals with "other factors" that were observed at the time of each specified loading event. The intent of including this information is to simply to identify certain factors that will be "questioned" by some users. Specific entries in this section of the worksheet include:

-	air temperature	(measured hourly onboard the Kulluk)
-	snow cover	(rough estimate from occasional photos and judgement)

These data entries are very straightforward and are not illustrated here. However, it should be noted that "snow cover data" for each event has simply been estimated and entered as light, moderate or heavy. These snow coverage terms are loosely defined as follows:

- light suggests less than 10 cm on average
- moderate suggests between 10 and 30 cm on average
- heavy suggests more than 30 cm, particularly where it has drifted in rough ice areas

Ice Management Support

The fourth grouping of data entries in the worksheet highlights the type of ice management support that was provided around the Kulluk during each event. These entries include:

- number of support vessels
- support vessels (ie: the specific vessels used)
- ice management technique

The reason for providing this data is to give the user some feel for the type of ice management system that was used during each event. Information about the number and "specifics" of the ice management vessels is straightforward, but the ice management techniques that were employed are not. It is not the intent of this work to discuss the different ice management techniques that were used. "Descriptive phrases" that are given in the data set include:

- as required breaking and "pushing" of floes
- the picket boat approach, circular updrift passes, and close passes
- linear and tandem tracks

Schematics that briefly highlight these ice management techniques are given in Appendix 1. An example of the type of "ice management data entries" that are contained in this portion of the Kulluk worksheet is given as follows.

Ice Management Support

Number of Vessels	***Support Vessels***	***Ice Management Technique***
2	- Ikaluk - Kalvik	break / push individual ice floes, as required
2	- Ikaluk - Kalvik	linear tracks, with occasional close passes
3	- Ikaluk - Miscaroo - Kalvik	picket boat approach
3	- ikaluk - Miscaroo - Terry Fox	tandem linear tracks

Managed Ice Conditions

The fifth grouping of data entries in the Kulluk worksheet highlights the type of managed ice conditions that were observed around the Kulluk during each event. These entries include:

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

The reason for providing this information is to give the user some feel for the type of broken ice conditions that resulted from ice management activities around the Kulluk, during each event. It also gives some feel for the effectiveness of ice management support in different types of ambient ice conditions, and is a reflection of the “actual ice regime” around the Kulluk as opposed to “updrift conditions in the far field”. The information that is available for these data entries is by no means exact. Occasional notes and photographs, in combination with a first hand knowledge of ice management targets and many of the event situations, were used as a basis for this input. “Harder data” used to be available from video recordings that were taken onboard the Kulluk, but these tapes have long since disappeared.

An example of the type of “managed ice conditions” entries that are contained in this portion of the Kulluk worksheet is given as follows.

Managed Ice Conditions

"Local" Ice Concentration (10ths)	*Mean Ice Thickness (m)*	*Thicker Ice Fragments (m)*	*Typical Managed Ice Piece Size (m)*	*Larger Managed Ice Piece Sizes (m)*	*Related Comments*
9+	0.6	0.6	5 - 20	30 - 60	managed ice in heavy pressure
10	0.6	0.6	500	500	unmanaged ice area
9+	1.2	3	30 - 60	60 - 100	managed ice area
9	1.2	2.5	10 - 30	30 - 60	well managed ice
9	2.5	10 - 20	20 - 30	40 - 60	heavy managed ice with some large thick ridge fragments

Peak Loading Event

The final group of entries in the Kulluk worksheet contains information about the magnitude and nature of the loads that the moored vessel experienced during each event, and details about the ice features and types of ice interactions that caused these loading events. Specific entries in this data set grouping include:

- 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

Reasonably good documentation about the type of ice interaction that occurred during each event was available but information about specific ice features was less certain and again had to be determined from various notes, photographs and judgements, on a “best guess basis”. The loading information, which is central to this work, is “hard data” that was measured by the Kulluk’s instrumentation system. As noted earlier, measured load values are considered to be good to within 15%. Here, it is important to mention that not all of the original Kulluk load records are still available in the form of detailed time series. However, for major portions of three of the five years of event information that were included in this data set, continuous strip chart records of global loads have been kept and were used in this work. This detailed data forms the basis for the data set entries regarding the nature of the loads, such as peak to mean ratios, rise times, and durations. Where time series records are no longer available, load magnitudes that were extracted from the original data and documented in earlier reports have been used in isolation, without related information about the specific nature of the load.

An example of the type of "load event" data entries that are contained in this final portion of the Kulluk worksheet is given as follows.

Peak Loading Event

Type of Interaction	***Best Guess Ice Thickness*** *(m)*	***Best Guess Ice Floe / Fragment Size*** *(m)*	***Peak Ice Load*** *(tonnes)*
large ice floe fragment impacts and splits	2.0	250 x 300	275
slurry flow	2.0	25	120
slurry flow	2.5	30	160
updrift rubble wedge	3.0	30	239

Ratio of Peak to Mean Ice Load	***"Rise Time" to Peak Load*** *(minutes)*	***Duration of Load Event*** *(minutes)*	***Comments***
-	-	-	a larger ice floe fragment
1.3	6	30	steady state condition
1.3	4	25	steady state condition
2	8	15	poor clearance and high loads in pressure

In the "type of interaction" column, a variety of descriptive terms have been used in the data set, such as "slurry flow, updrift rubble wedge, unbroken and floe impact". These terms are not defined here, but are explained in Section 5, where summary results are presented on the basis of "exercising" the data set. Similarly, the manner in which load ratios, rise times and event durations have been defined is also highlighted in Section 5, in conjunction with related summary results.

In total, 384 loading events have been extracted from the Kulluk information and are included in the "Kulluk component" of full scale data set. These loading events, which span five years of Beaufort Sea operations, were selected to provide representative information on full scale loads across a wide range of moving pack ice conditions and ice interaction situations. A complete listing of this Kulluk data is given in on a zip disk, which has been submitted as a separately to this report.

4.4 Ship Data Entries

Because of limitations in its quantity, quality and completeness, the ship data that has been included in the full scale data set is viewed as a secondary source of loading information, as compared to the Kulluk data. The highest quality ship data that has been used in this study comes from icebreaker performance trials in broken ice channels, as noted earlier. All of this ship data was fully screened for acceptability in previous work (Keinonen et al, 1989, 1991, 1996) and reanalysed in a consistent manner. Twenty of the data points, covering slow speed performance trials for eight different icebreakers, are included in the ship component of the full scale data set. All of the ship operating events that are contained in Canmar's JIP study were also reviewed, to determine their value in terms of the full scale data set. Of the twenty one original events treated in the Canmar study, less the Kulluk events that have been more thoroughly covered in this work, only six events are considered "sufficiently well defined and documented" to be of any real value here.

As noted earlier, the specific data set entries from ship trials and from other ship operations do not follow the "logic" that is given in Figure 4.1 quite as easily as the Kulluk information. Moreover, the loading events that were extracted from Canmar's JIP are quite "complex" in nature, more complex than can be described clearly in the data set table. Because of this, more detailed notes are provided in Appendix 2 for each one of the JIP ship events, to give some additional background. Despite these differences, the same types of entries have been included in ship component of the full scale data set, with a few modifications. These data set entries are outlined as follows.

Performance Trials

The twenty data entries from full scale performance trials contain data for eight different vessels travelling at speeds of less than 3 m/sec in their own previously broken (and unfrozen) channels. The vessels were the Kigoriak, Ikaluk, Kalvik, Franklin, Louis S. St. Laurent, Ann Harvey, Katmai Bay, and Otso/Kontio. The data entries in the "icebreaker trials portion" of the "ship worksheet" are similar to those for the Kulluk, and are very simply highlighted as follows.

- ice thickness, piece size and coverage
- ice strength and ambient temperature
- snow thickness
- channel width relative to vessel
- vessel speed

- vessel powering and thrust information that can be used for resistance and net thrust predictions

In all cases, flexural ice strength values (or an ice strength index or equivalent beam strength) were determined from through-ice temperature salinity profiles. In no cases were the broken channels affected by far field influences. This type of data was available for all of the ship trials, with the following exceptions.

- channel width (or managed width) was not recorded in most of the trials. Therefore, it was reasonably assumed that the channel width was equal to, or just slightly greater than vessel beam.

- ice piece size was only noted for a few of the trials. Therefore, it was assumed that ice piece sizes were in the range of 2-5 times the ice thickness, placing the average piece size at approximately 15-20% of vessel beam.

Most of the other "event" documentation for the ship trials data entries is straightforward, but not necessarily complete. For example, a column was added to specify the "ice drift track curvature", since this is known to affect the loads on vessels with length/beam ratios greater than one. However, this column was not used for the ship trials data, because turning tests (which are equivalent to situations with ice drift track curvature) were not carried out in broken ice.

Canmar's JIP Event Data

Data from the six "credible events" that are contained in Canmar's JIP study is also included in the full scale data set. The format for these data set entries is the same as for the ship trials and Kulluk information, although but the entries are far from complete due to limited documentation. Typically, this component of the ship worksheet contains data entries which:

- describe the vessel or vessels involved in the event
- give the date and time of each event
- describe the type of event in general terms
- describe the ambient ice conditions and ice management support
- provide an equivalent level ice thickness for the ice situation that was causing the event (sometimes in place of a best estimate of the actual ice thickness)
- provide a load estimate for the event

As mentioned earlier, additional background notes for these events are given in Appendix 2, where the derivation of the estimated load magnitudes is also described.

A complete listing of the ship data set entries for both the performance trials and Canmar's JIP events is also given on the zip disk, which is separate to this report.

4.5 Vessel & Mooring System Characteristics

There are two other worksheets in the Excel workbook that contains the full scale load event data set. These worksheets provide:

- details about the characteristics of the Kulluk and the other vessels for which load event information is given
- details about the characteristics of the Kulluk's mooring system at each location where load event information is given

Typical examples of the type of information that is provided in these "vessel characteristics" and "Kulluk mooring system" worksheets are shown as follows. It should be noted that all of the loading events in the Kulluk and ship data set worksheets are cross referenced to the specific vessel characteristics and mooring system descriptions.

Vessel Characteristics

Vessel Name	Kulluk	Kigoriak
Vessel Type	drilling barge	icebreaker
Ice Class	ASPPR 4	ASPPR 3
Design Particulars		
length LWL (m)	70	84.2
beam (m)	70	19.25
draft (m)	12.5	8.5
displacement (tonnes)	28,000	6,616
block coefficient	-	0.55
waterline diameter (if applicable)	70	-
ave. bow buttock angle (degrees)	23	24.1
ave. bow flare angle (degrees)	75	58.5
hull type (chined / smooth)	-	chined
reamer width each side (m)	0	1

	Kulluk	Kigoriak
Design Particulars (continued)		
% parallel middle body	0	67
side slope (degrees)	-	0
bow wedge	-	no
hull condition	zebron	bare steel
drive system	-	geared diesel
no. of propellers	-	1
propeller type	-	ducted C.P.
propeller diameter (m)	-	5.3
no. of rudders	-	1
total shaft power (MW)	-	12.2

Kulluk Mooring System Characteristics

Location:	***Amauligak 2J - 44***
water depth	32m
number of lines	9
line diameter	*3 1/2"*
line type	wire rope
breaking strength	520 tonnes

Line Number	*Length (m)*	*Orientation (degrees true)*	*Pretension (tonnes)*	*Anchor(s)*
line 1	-	-	-	
line 2	639	164	195	9T Bruce, 9T Bruce
line 3	772	196	200	15T Bruce
line 4	-	-	-	
line 5	732	255	210	9T Bruce, 6.5T Bruce
line 6	530	285	60	15T Bruce
line 7	666	314	220	15T Bruce
line 8	-	-	-	
line 9	621	14	210	15T Bruce
line 10	601	45	180	15T Bruce
line 11	723	76	150	15T Bruce
line 12	584	106	70	15T Bruce, 9T Bruce

Again, complete listings of the vessel characteristics and Kulluk mooring system information that is contained in the full scale data set are given on the zip disk, separate to this report.

5.0 Full Scale Data Assessment

5.1 General

In this section of the report, some of the results that have been obtained by "exercising" the data set are given. As outlined earlier, the intent of this assessment is to provide a summary of the full scale load data that has been obtained from moored vessels and from other ship operations in pack ice, in the form of "scatter plots". Here, it is important to note that this assessment is not intended to be "all embracing", since the main effort has been directed towards developing the data set itself. However, the assessment is sufficiently thorough to highlight the major trends and "features" that are indicated by the full scale load data.

Because the Kulluk information comprises the vast majority of the full scale data set, it has been treated in the highest level of detail. As such, the Kulluk data forms the "backbone" for this assessment. The more limited full scale load information that has been gleaned from ship trials and other ship operations has simply been compared to the Kulluk data, to see whether or not the information from different sources ties together in a sensible manner and forms a consistent pattern.

5.2 Kulluk Data

In order to summarize the Kulluk load data, the approach that was taken was to identify a number of logical "areas of interest", then evaluate the full scale Kulluk information on this basis. The interest areas that were identified, and the implications of the Kulluk data assessed in the context of these areas of interest, are highlighted as follows.

5.2.1 Loads in Level Ice

The Kulluk was originally designed to operate in unbroken level ice to a thickness of 1.2m, without the need for any ice management support. However, it was recognized that ice management would "almost always" be required to ensure prudent stationkeeping operations with the Kulluk, because Beaufort Sea pack ice is typically rough, with frequent areas of ridging and rubble interspersed throughout the ice cover. Accordingly, the Kulluk usually operated in managed ice conditions and there were only a few instances in which the Kulluk was "allowed" to operate in level ice, without it being prebroken by support icebreakers.

Notwithstanding these comments, there are a number of loading events in the full scale Kulluk data set that involve unmanaged ice conditions. This event data was used to assess the range of loads that the Kulluk experienced in situations where the ice cover had not been prebroken by support icebreakers.

Figure 5.1 shows the peak loads that were measured in these level ice interaction situations, in ice thicknesses up to 1.2m. Although there is some scatter in the data, there is a clear trend for increasing loads with increasing ice thicknesses. However, it should be noted that these loads involved ice interactions at different times of the year and in different years, and hence, in differing ice strength and ice friction conditions. In order to "correct" for any variations in load levels that may have been caused by these influences, the ice strength and temperature information that is contained in the data set was used to normalize the measured loads in level unbroken ice, on an event by event basis. The normalization approach that was taken is based upon a vessel resistance prediction formula (Keinonen et al, 1996) which is further described in Section 5.3.1 This formulation includes correction terms for a variety of parametric dependencies, including:

- strength influence on load is proportional to: $0.63 + 0.00074\,\sigma_f$

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

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

In Figure 5.2, the Kulluk load data obtained in level unbroken ice is again shown, normalized to a flexural strength of 500 kPa. In Figure 5.3, a second correction factor has been included to account for frictional influences, normalized to a temperature of - 10°C. It may be seen that this normalization procedure tends to reduce the scatter in the level ice load data a little, and brings "slightly more order" to the load versus ice thickness scatter plot.

An "upper bound" to the normalized full scale Kulluk load data is also shown in Figure 5.3. This bound was calculated by grouping the load data into thickness bins, calculating mean and standard deviation values for the loads in each bin, determining a load value for each bin at the mean plus two standard deviation level (ie: a 95.5% non-exceedence value), then fitting a "best fit line" through the resultant load values with a linear regression analysis. As such, the bounding line that is shown is intended to be a reasonable upper bound that recognizes the intrinsic scatter in the data, is not overly conservative, and is statistically based.

This level ice loading data has also been used to assess the possible influence of ice drift speed on load levels. In order to "correct" for ice thickness effects, the loads have been normalized to a level ice thickness of 1m (for ice > 0.15m thick) on the basis of a best line fit through the load versus thickness plot in Figure 5.3. The results are shown in Figure 5.4, in the form of a load versus drift speed scatter plot. It may be seen that there is no obvious effect of ice drift speed on the load levels that the Kulluk experienced. Accordingly, the data suggests that ice drift speed is very much a secondary influence on loads, compared to the effect of thickness.

5.2.2 Loads in Unbroken Ridges

On the basis of model tests carried out during the Kulluk's design phase and prior experience with other vessels in ice, it was well known that load levels in unmanaged ridges could be very high. As a result, ice management was "always used" to fragment the ridges that were approaching the Kulluk, although a few did "escape" this operation. Because of this, there are a handful of cases that involve small unbroken ridges in the Kulluk data set.

The peak loads that were measured during these ridge interaction events are shown in Figure 5.5. Although the number of data points is extremely limited, they do show a strong trend for higher loads with larger ridge thicknesses, as one would expect. Again, the loads that are given in this figure are not corrected for possible variations in ice strength and friction. In addition, it is quite likely that the ridge load data contains variations because of differences in consolidated layer thicknesses. However, any variations of this nature are impossible to pursue, because the consolidated layer thicknesses in the ridges that interacted with the Kulluk are not known.

In the case of ridges, none of these effects are straightforward to attempt to accommodate. Here, it has been very simply assumed that strength and friction influences on the total ridge load follow the same proportionalities as for the level ice case, and measured ridge load levels have been adjusted on this basis. The resultant load data, normalized in this manner, is shown in Figure 5.6. It may be seen that this normalization procedure does not make much difference in the trend that is indicated. Because of the limited amount of ridge load information in the Kulluk data set, no upper bound or best line fits have been developed with the data. The reason for this is related to the author's view that any projections made from these types of fits could be misleading, particularly at large ridge thicknesses. It is important to recognize that the data only covers small ridges (sail heights < 2m) in which the relative thicknesses of the consolidated layer and keel rubble are not known. However, it is also important to recognize that this full scale ridge loading information is unique, since similar data has not been obtained for other moored vessels anywhere in the world, to date.

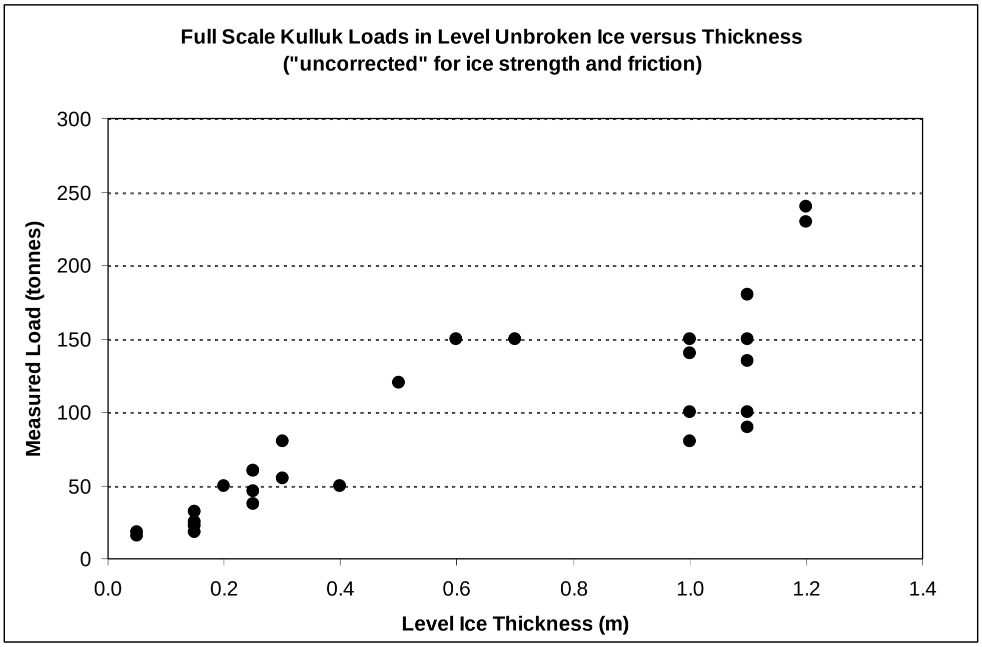


Figure 5.1

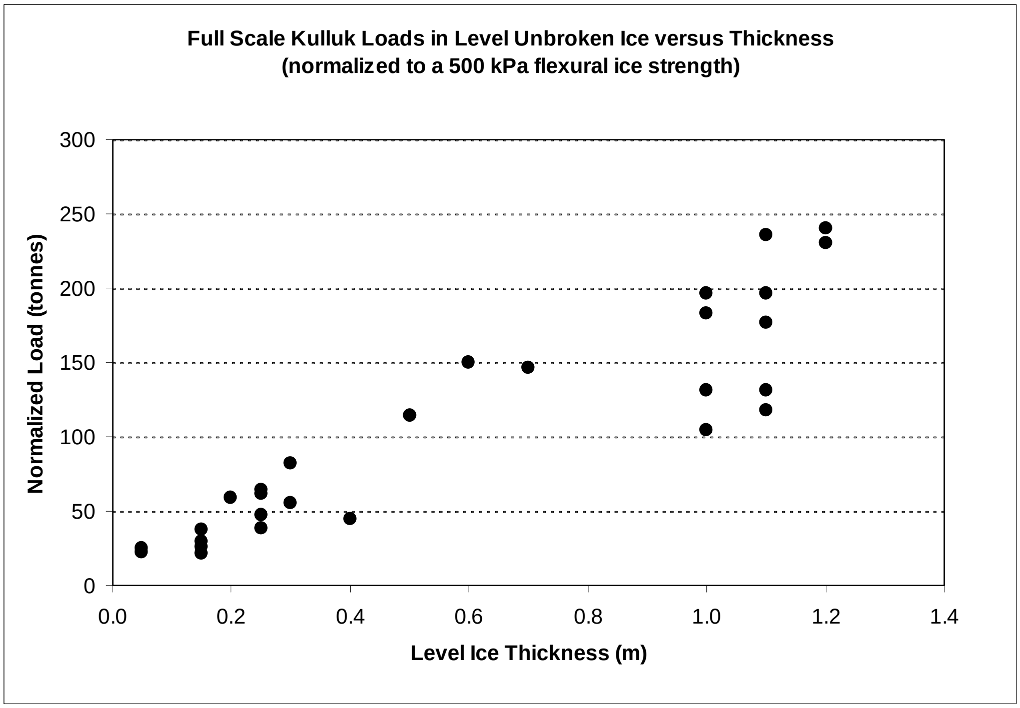


Figure 5.2

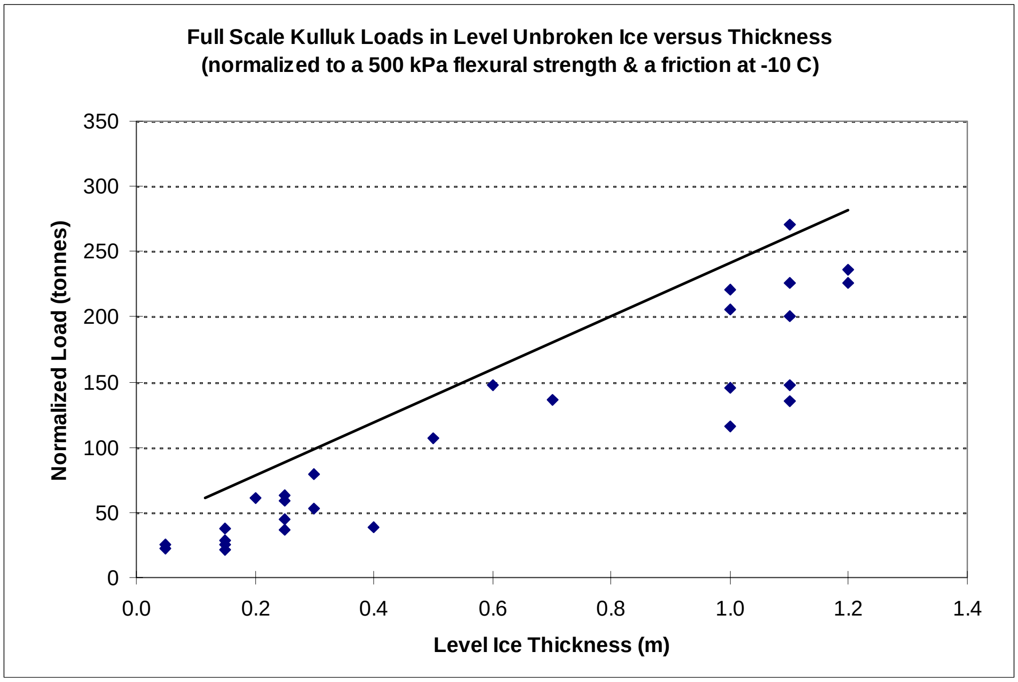


Figure 5.3 **The upper bound line to these level ice loads is described by y = 204 x + 37.**

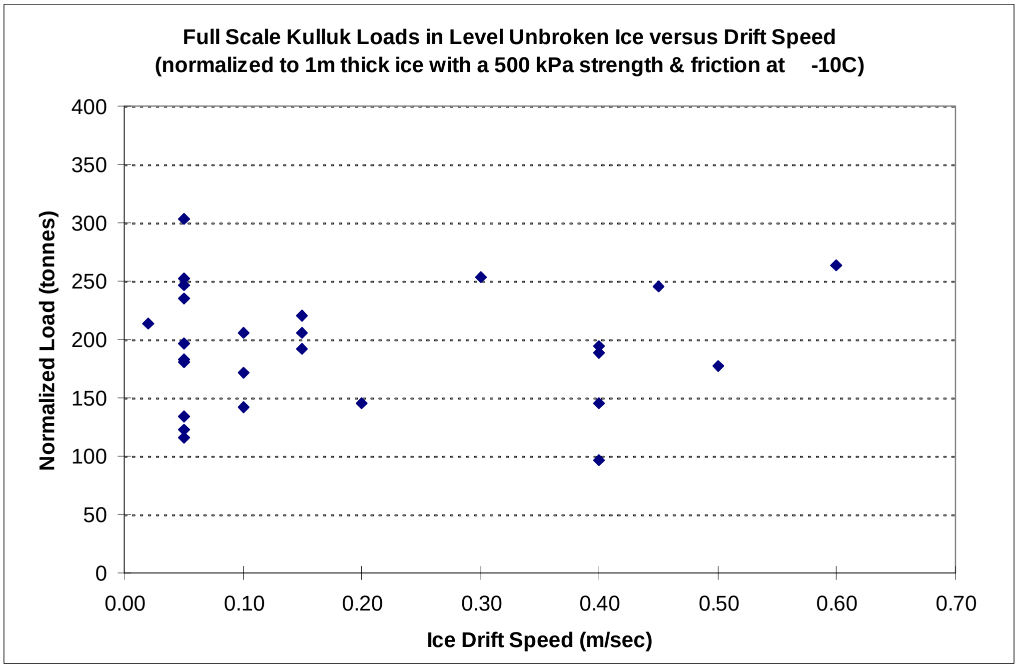


Figure 5.4

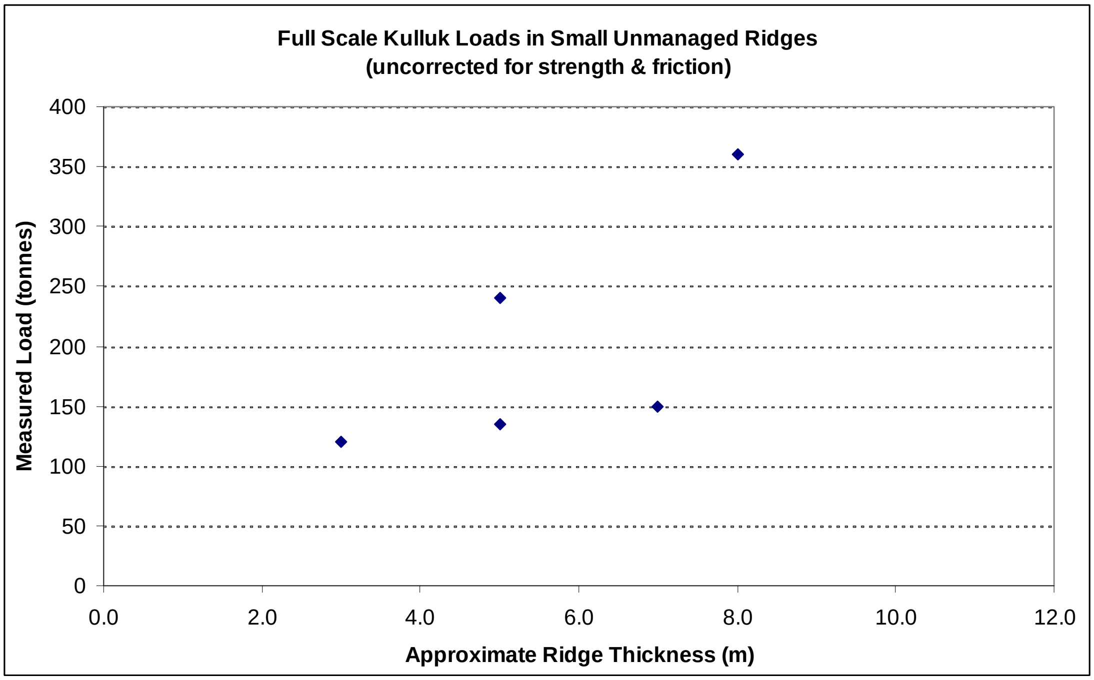


Figure 5.5

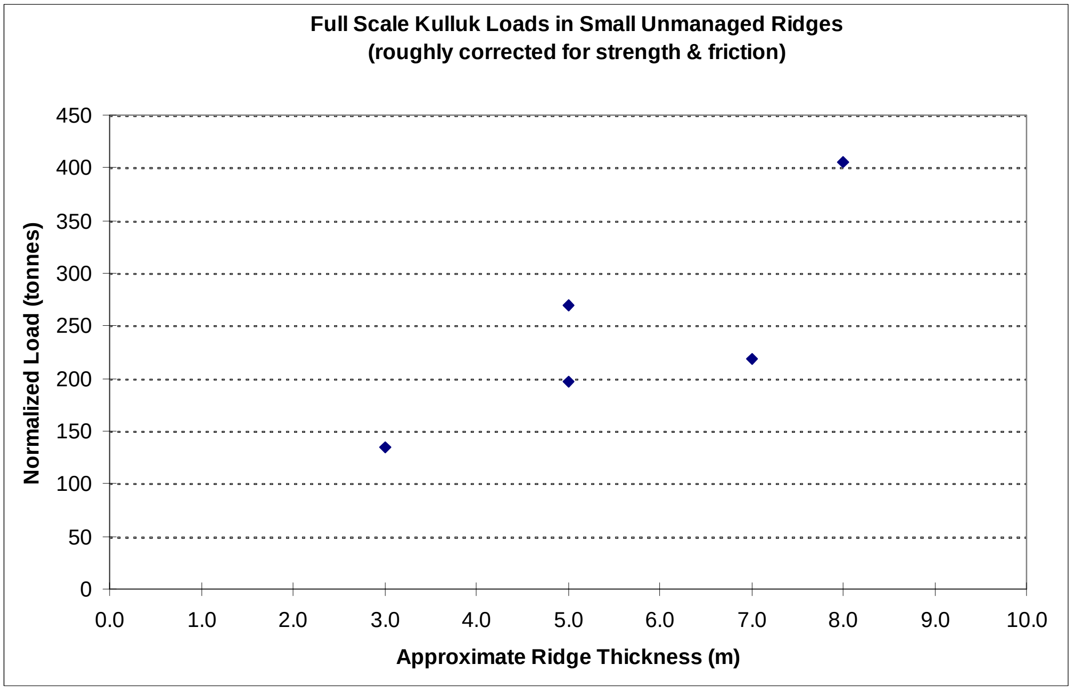


Figure 5.6

5.2.3 Loads in Managed Ice with Good Clearance

As noted earlier, the Kulluk generally operated in managed ice conditions, with the support icebreakers prebreaking the oncoming ice cover into "small ice floe fragments". When ice that was of any significance was present around the vessel, the Kulluk ice management guidelines called for managed ice piece sizes that were in the range of 50m, as a target. As a result, the vast majority of loading events that are contained in the full scale Kulluk data set were experienced in managed ice conditions.

Figure 5.7 shows the loads that were measured on the Kulluk, plotted against the thickness of the managed ice fragments that were moving against it. The load data that is included in this figure only involves ice interaction events where "good ice clearance" was seen around the Kulluk. Situations involving "tight" managed ice conditions with poor clearance, or those involving ice pressure, have been treated separately since these types of events gave rise to different ice interaction behaviours and in turn, different load levels.

This figure contains Kulluk load data across the full range of ice concentrations that were encountered, and is uncorrected for possible variations related to differing ice strength or friction effects. It can be seen that the plot spans a wide range of ice thicknesses, from very thin level ice fragments to rough managed ice areas, with typical ridge and rubble fragment thicknesses up to 10m. Although there is considerable scatter in the data, there is a clear trend for higher load levels with larger managed ice fragment thicknesses, as one would expect.

In Figure 5.8, the same loading data is shown, but normalized to accommodate for possible variations in friction (to - 10°C, according to the procedure outlined in Section 5.3.1). Here, no attempts have been made to correct for possible variations due to ice strength influences, because the ice had been prebroken by the support icebreakers and was simply "flowing" around the Kulluk's hull as a "slurry" (see Figure 5.9). It may be seen that this normalization procedure has some effect in terms of rearranging the data, but it is not significant. An upper bound to the normalized Kulluk load data is also shown in Figure 5.9. As in the level ice case, this bounding line was calculated by grouping the load data into thickness bins, calculating the mean and standard deviation values for the loads in each bin, determining a load value for each bin as the mean plus two standard deviations, then fitting a best-fit line to the resultant load values. Again, this approach is intended to form a reasonable upper bound to the data.

The main point that should be made at this stage is the significant benefit of ice management, in terms of load reductions. By comparing the load data and bounding line given in Figure 5.8 with the level ice loading data shown in Figure 5.3, it may be seen that load levels in managed ice are about five times less than in unbroken ice, for the same ice thickness.

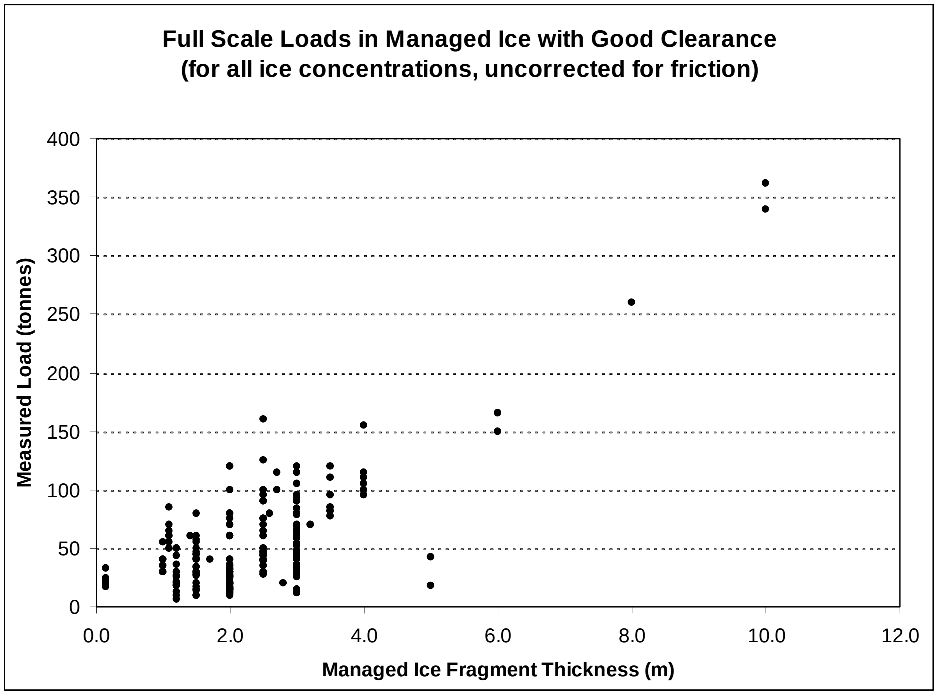


Figure 5.7

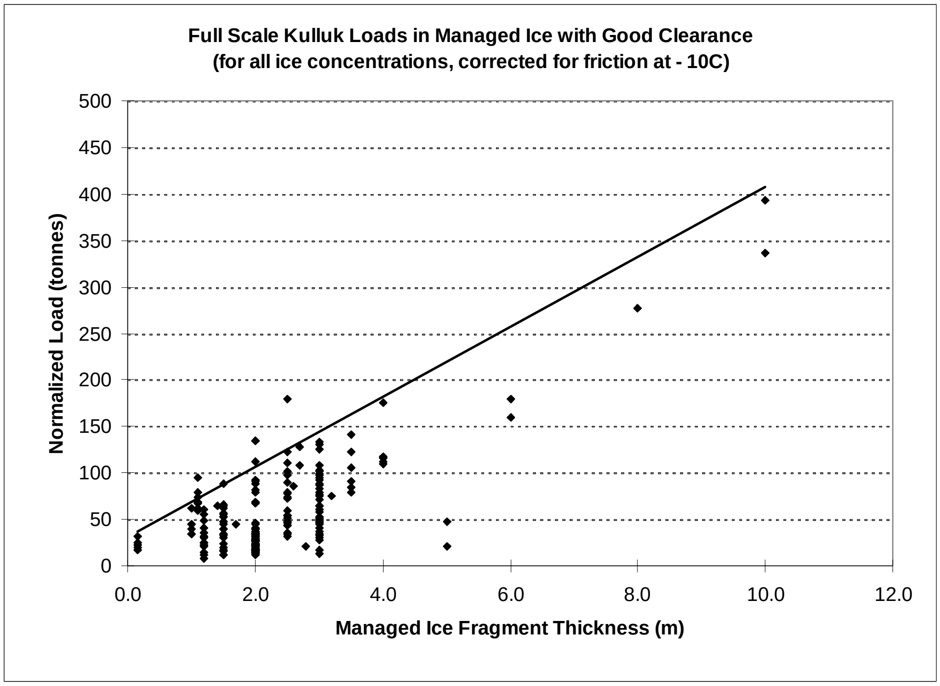


Figure 5.8: The upper bound line to these loads in managed ice with good clearance is described by y = 38x + 31.

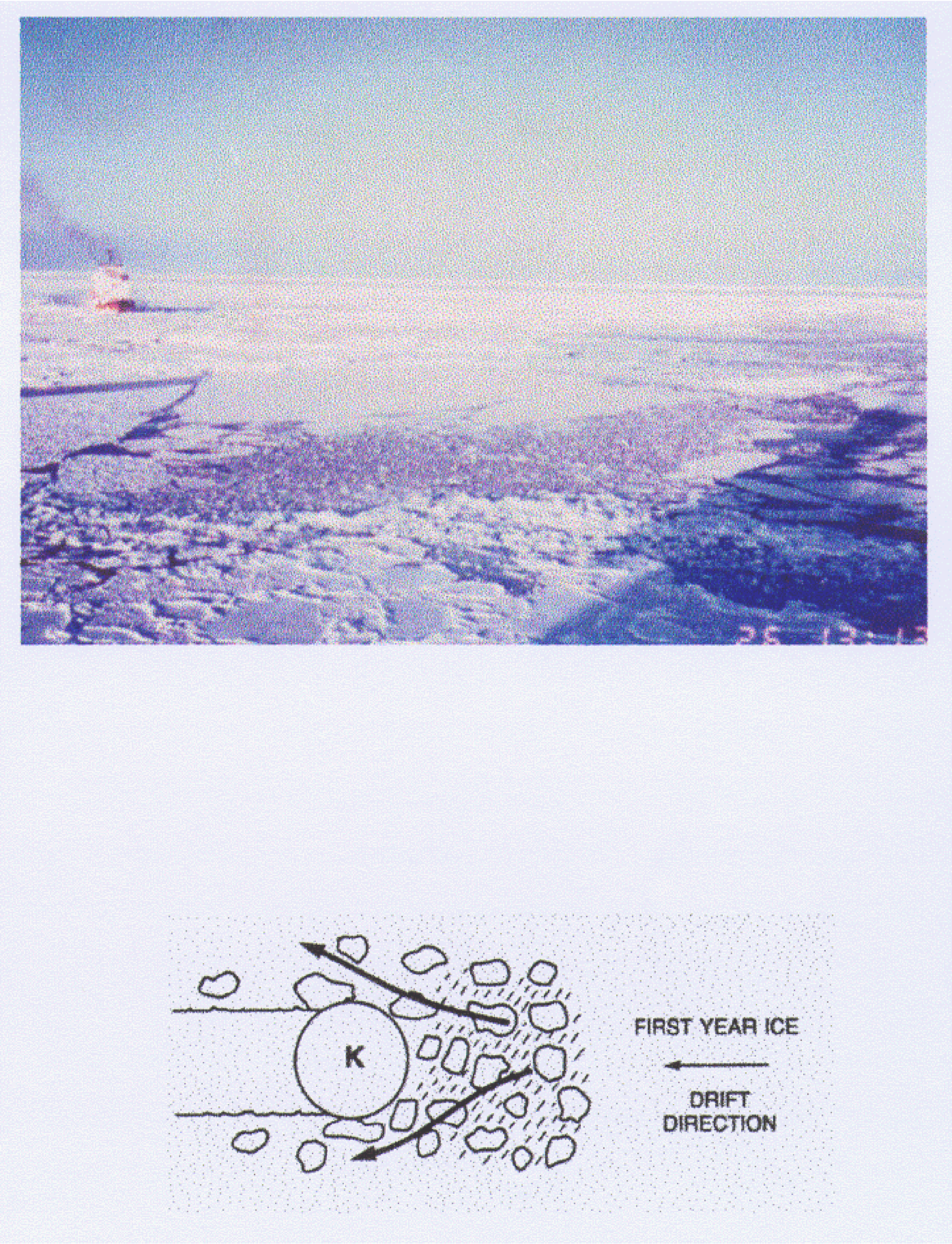


Figure 5.9 **The upper photo provides a representative example of good ice clearance (or “slurry flow” conditions) around the Kulluk. The managed ice fragments are clearing well, without any evidence of an updrift “rubble wedge” forming.The lower figure is a schematic illustration of this situation.**

This Kulluk load data, in managed ice conditions with good clearance, has also been plotted in its normalized form to provide some feel for the effect of varying ice concentrations, ice drift speeds and managed ice fragment sizes on the load levels that were experienced. Because of the large number of load events that are available in the data set, it was possible to group the event data into fairly tight thickness categories to negate the influence of ice thickness, then plot the load data against different ice parameters on this basis. The scatter plots that were generated in this way are summarized as follows.

- Figures 5.10 to 5.12 show full scale loads in managed ice with good clearance as a function of ice concentration, for six different ice thickness categories, across all observed ice drift speeds and managed ice fragment sizes

- Figures 5.13 to 5.15 show full scale loads in managed ice with good clearance as a function of ice drift speed, for the six different ice thickness categories, across all observed ice concentrations and managed ice fragment sizes

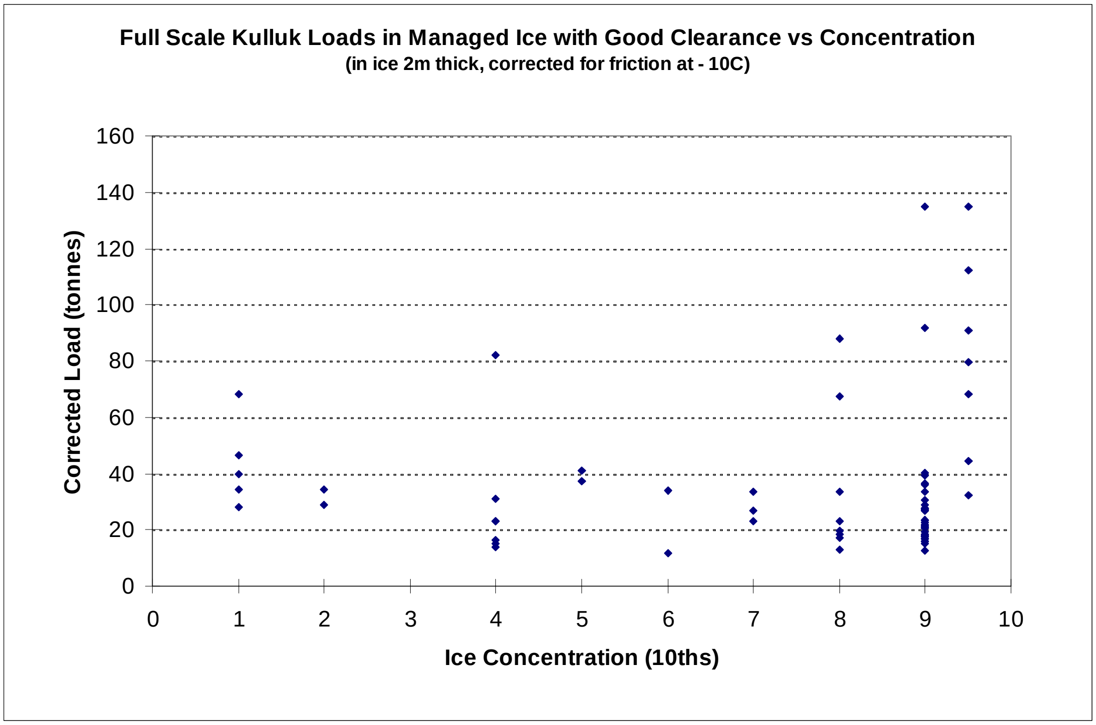
- Figures 5.16 to 5.18 show full scale loads in managed ice with good clearance as a function of ice fragment size, for the six different ice thickness categories, across all observed ice concentrations and drift speeds

The main points that can be made on the basis of the information that is given in these figures are outlined as follows.

- load levels tend to increase with increasing ice concentrations, as one would expect. The relatively high loads that are sometimes seen at lower concentration levels are probably more a reflection of "higher concentration clusters" of managed ice moving past the Kulluk, than sizable loads generated by individual floe fragment impacts.

- any effect of ice drift speed, at least over drift speeds up to 0.6-0.7 m/sec, is not apparent from the load data and therefore, drift speed should not be considered as a significant influence on load levels for low to moderate drift speed events (although it does affect the ability of the ice management system to "keep up", and hence the piece size)

- the data does not indicate any significant influence of managed ice piece size on the load levels that were seen, although there is not much of a spread in the managed ice fragment sizes observed (typically 20m to 40m). In general terms, this reflects the ability of the Kulluk's ice management vessels to effectively deal with most of the pack ice situations that were encountered. There is, however, a slight tendency for managed ice fragment sizes to increase with greater ice thicknesses.


Full Scale Kulluk Loads in Managed Ice with Good Clearance vs Concentration
(in ice 2m thick, corrected for friction at - 10C)
Corrected Load (tonnes)
0
20
40
60
80
100
120
140
160
Ice Concentration (10ths)
0
1
2
3
4
5
6
7
8
9
10

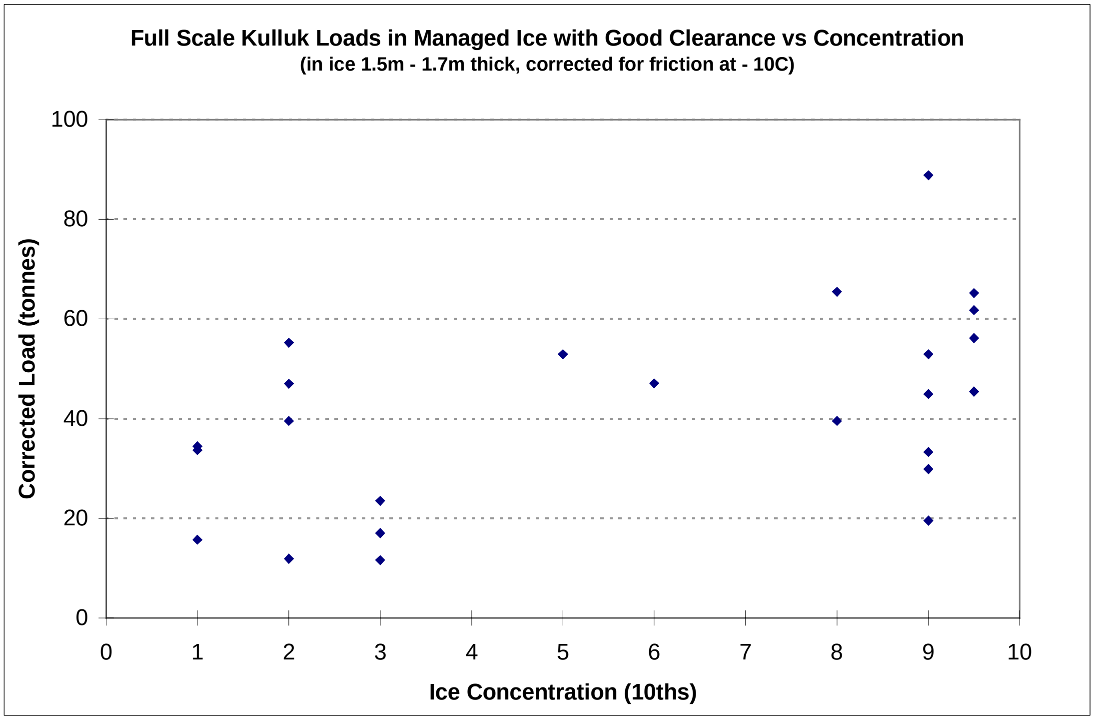
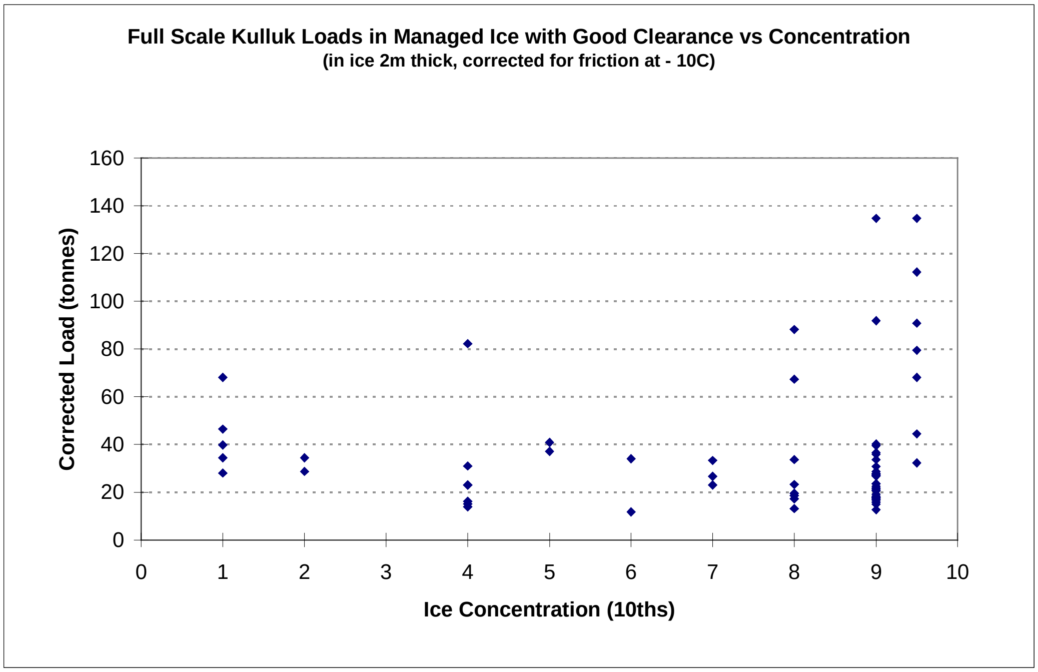

Full Scale Kulluk Loads in Managed Ice with Good Clearance vs Concentration
(in ice 1.5m - 1.7m thick, corrected for friction at - 10C)
Corrected Load (tonnes)
0
20
40
60
80
100
Ice Concentration (10ths)
0
1
2
3
4
5
6
7
8
9
10

Figure 5.10:


Full Scale Kulluk Loads in Managed Ice with Good Clearance vs Concentration
(in ice 2m thick, corrected for friction at - 10C)
Corrected Load (tonnes)
0
20
40
60
80
100
120
140
160
0
1
2
3
4
5
6
7
8
9
10
Ice Concentration (10ths)

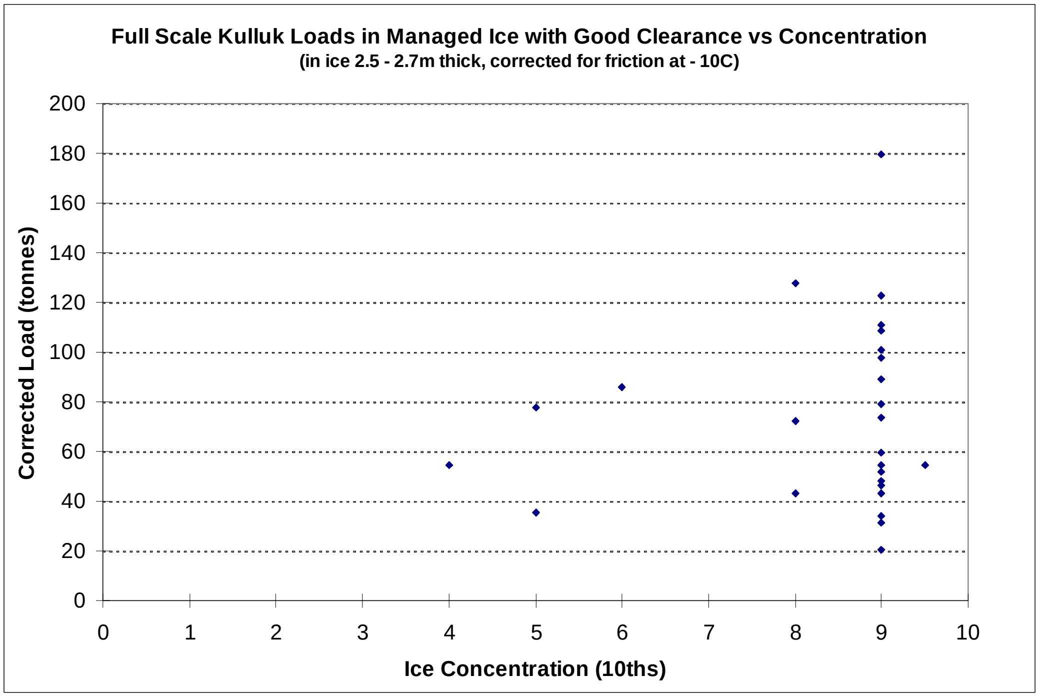
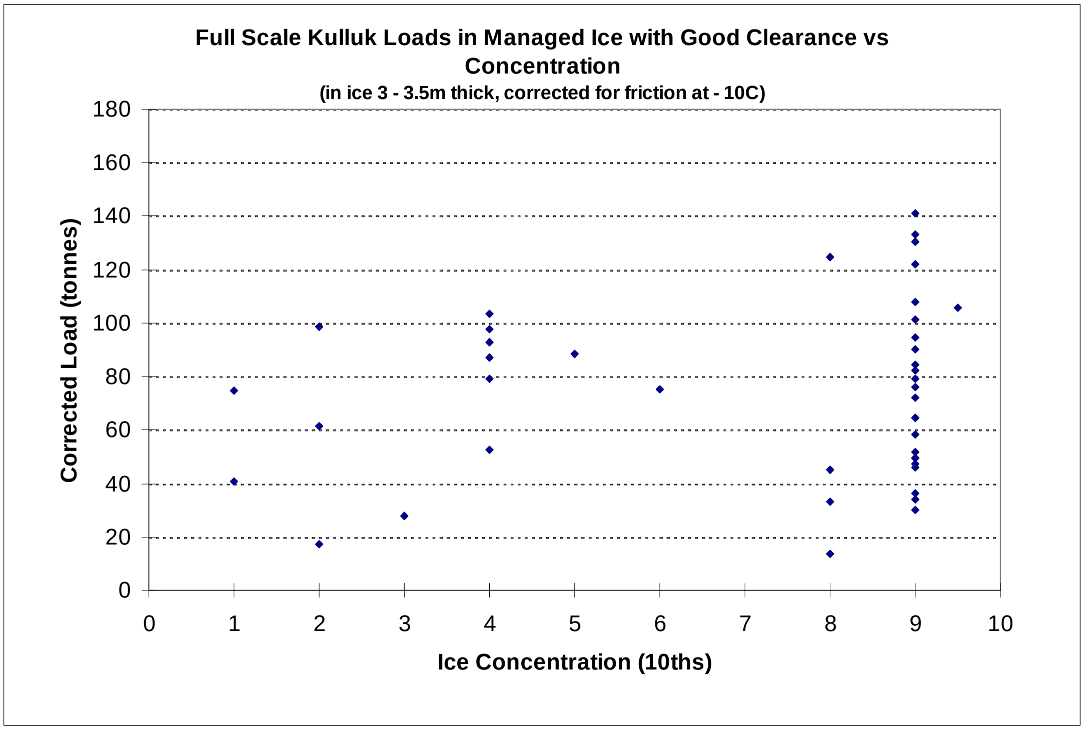

Full Scale Kulluk Loads in Managed Ice with Good Clearance vs Concentration
(in ice 2.5 - 2.7m thick, corrected for friction at - 10C)
Corrected Load (tonnes)
0
20
40
60
80
100
120
140
160
180
200
0
1
2
3
4
5
6
7
8
9
10
Ice Concentration (10ths)

Figure 5.11


Full Scale Kulluk Loads in Managed Ice with Good Clearance vs Concentration
(in ice 3 - 3.5m thick, corrected for friction at - 10C)
Corrected Load (tonnes)
0
20
40
60
80
100
120
140
160
180
Ice Concentration (10ths)
0
1
2
3
4
5
6
7
8
9
10

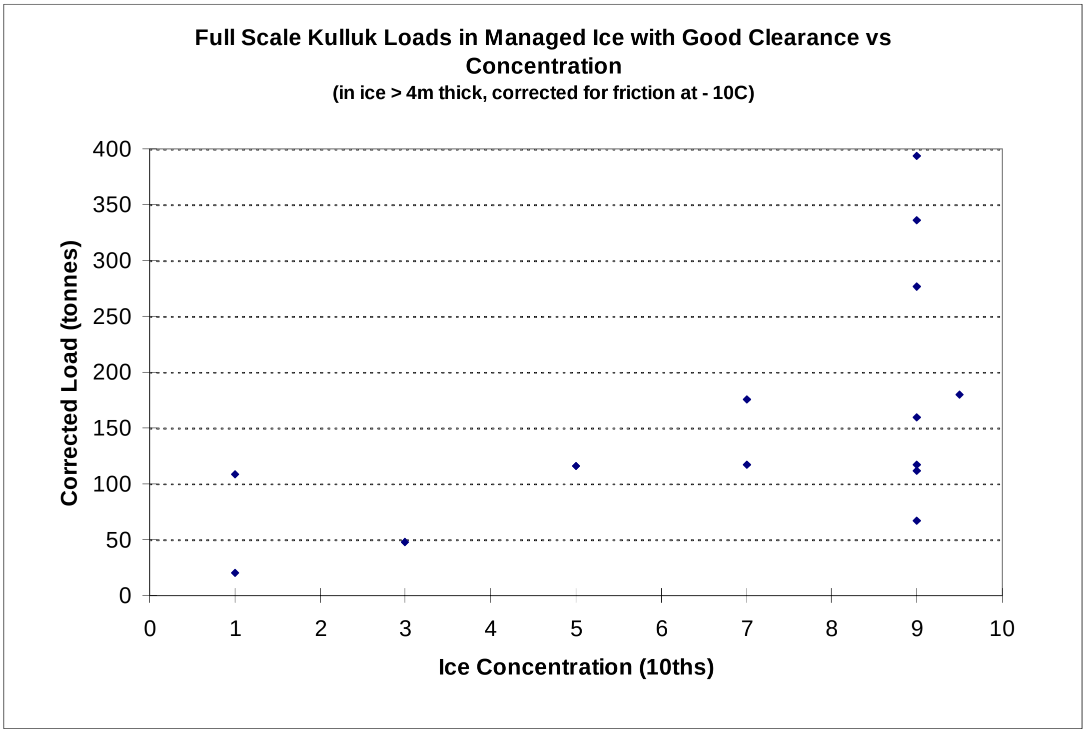

Full Scale Kulluk Loads in Managed Ice with Good Clearance vs Concentration
(in ice > 4m thick, corrected for friction at - 10C)
Corrected Load (tonnes)
0
50
100
150
200
250
300
350
400
Ice Concentration (10ths)
0
1
2
3
4
5
6
7
8
9
10

Figure 5.12

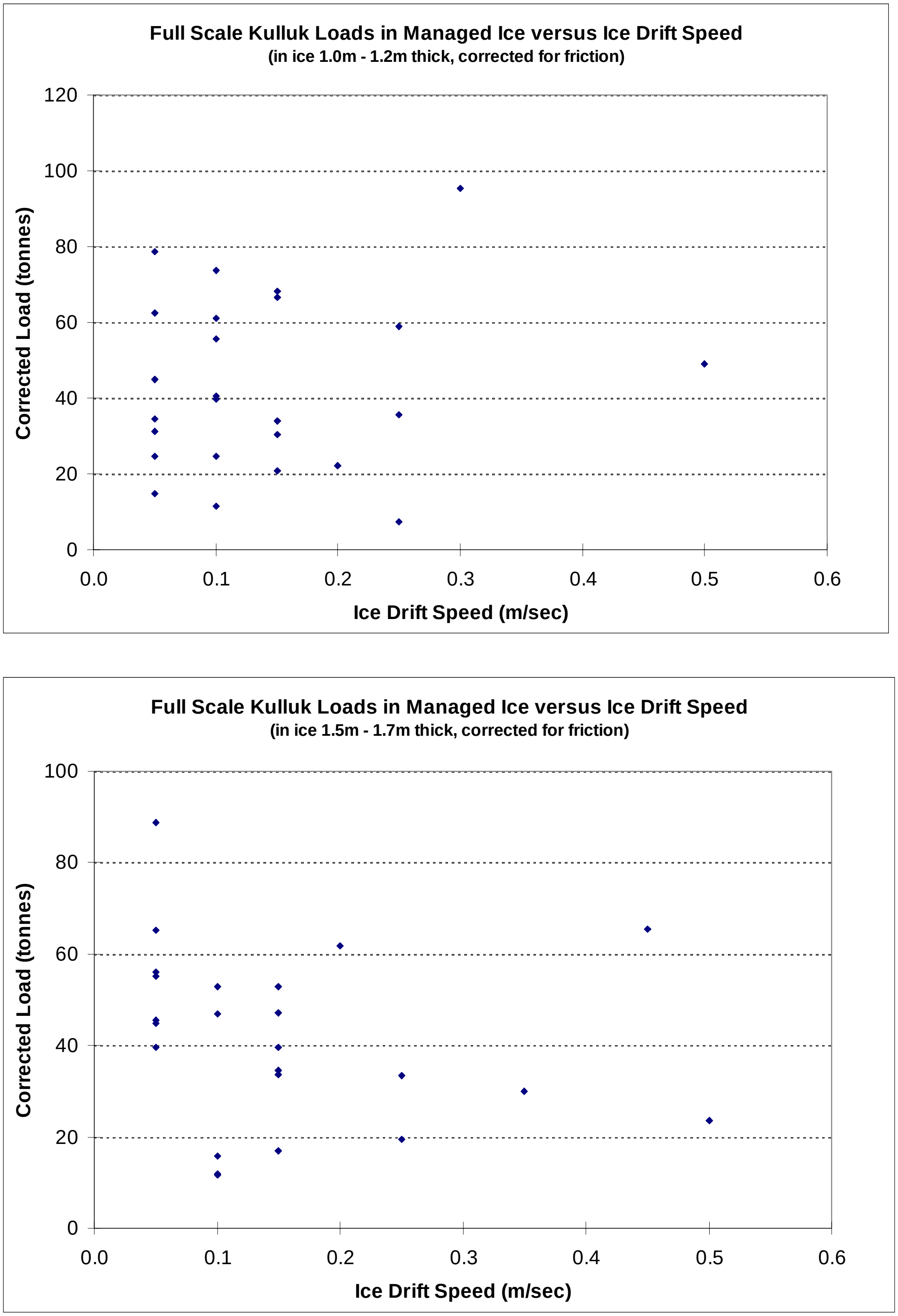
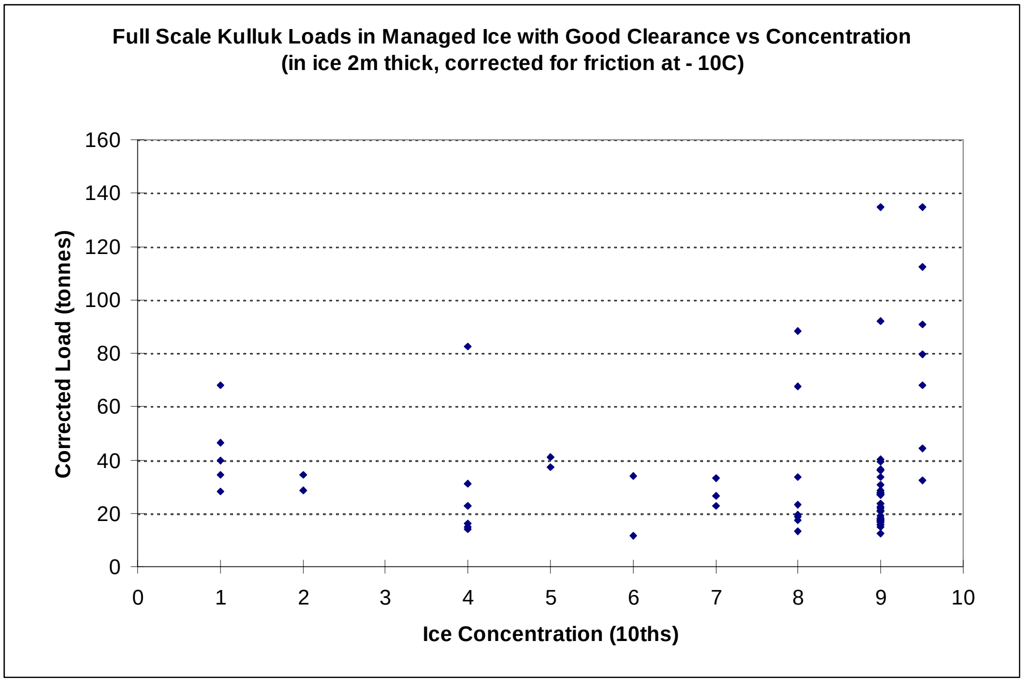

Full Scale Kulluk Loads in Managed Ice versus Ice Drift Speed
(in ice 1.0m - 1.2m thick, corrected for friction)
Corrected Load (tonnes)
0
20
40
60
80
100
120
Ice Drift Speed (m/sec)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
Full Scale Kulluk Loads in Managed Ice versus Ice Drift Speed
(in ice 1.5m - 1.7m thick, corrected for friction)
Corrected Load (tonnes)
0
20
40
60
80
100
Ice Drift Speed (m/sec)
0.0
0.1
0.2
0.3
0.4
0.5
0.6

Figure 5.13


Full Scale Kulluk Loads in Managed Ice with Good Clearance vs Concentration
(in ice 2m thick, corrected for friction at - 10C)
Corrected Load (tonnes)
0
20
40
60
80
100
120
140
160
0
1
2
3
4
5
6
7
8
9
10
Ice Concentration (10ths)

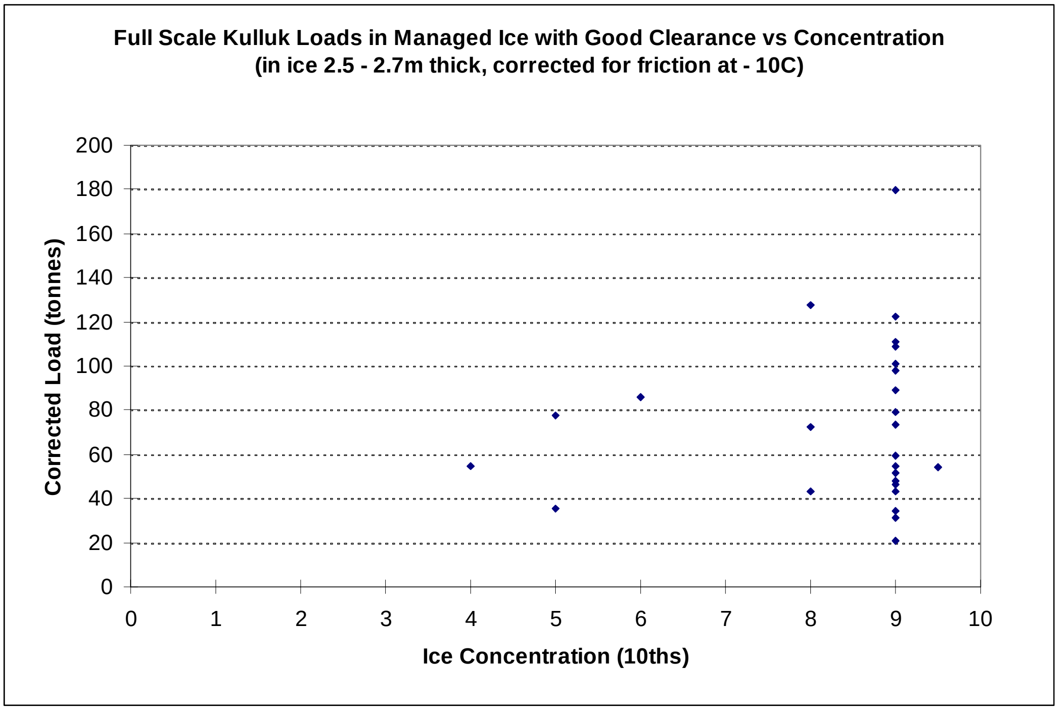
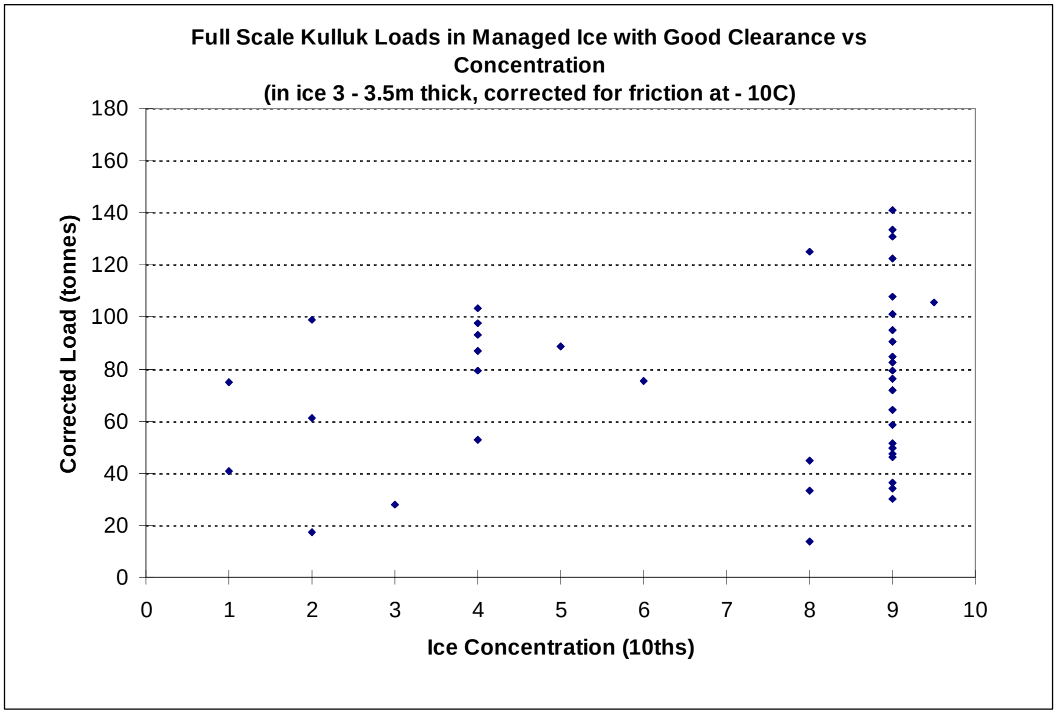

Full Scale Kulluk Loads in Managed Ice with Good Clearance vs Concentration
(in ice 2.5 - 2.7m thick, corrected for friction at - 10C)
Corrected Load (tonnes)
0
20
40
60
80
100
120
140
160
180
200
0
1
2
3
4
5
6
7
8
9
10
Ice Concentration (10ths)

Figure 5.14


Full Scale Kulluk Loads in Managed Ice with Good Clearance vs Concentration
(in ice 3 - 3.5m thick, corrected for friction at - 10C)
Corrected Load (tonnes)
0
20
40
60
80
100
120
140
160
180
0
1
2
3
4
5
6
7
8
9
10
Ice Concentration (10ths)

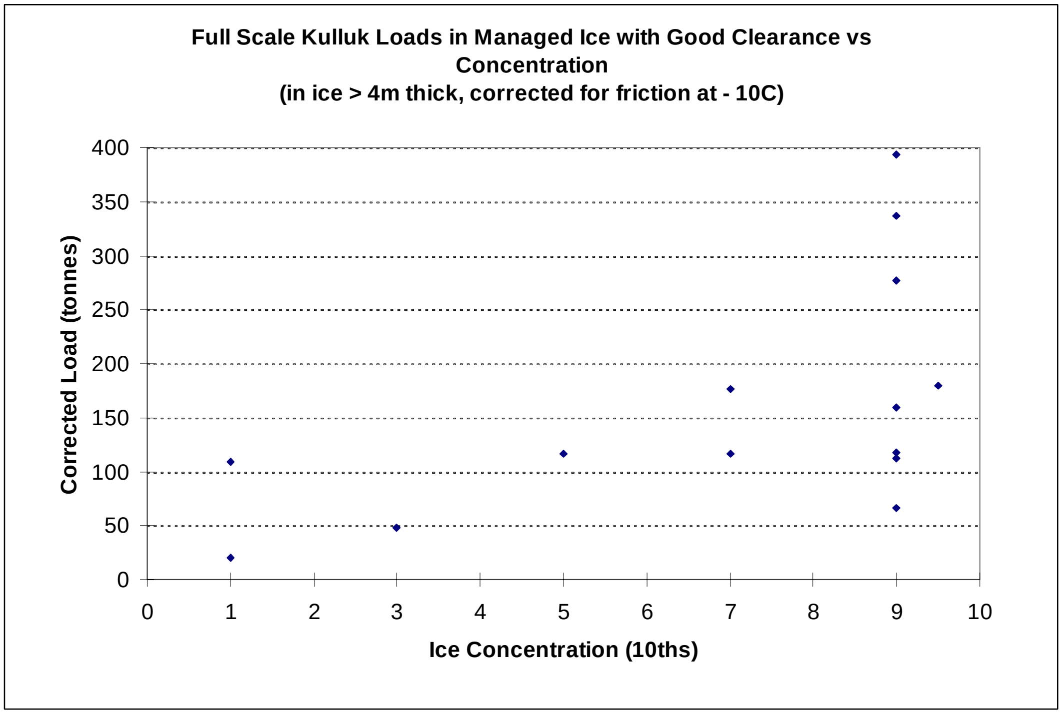
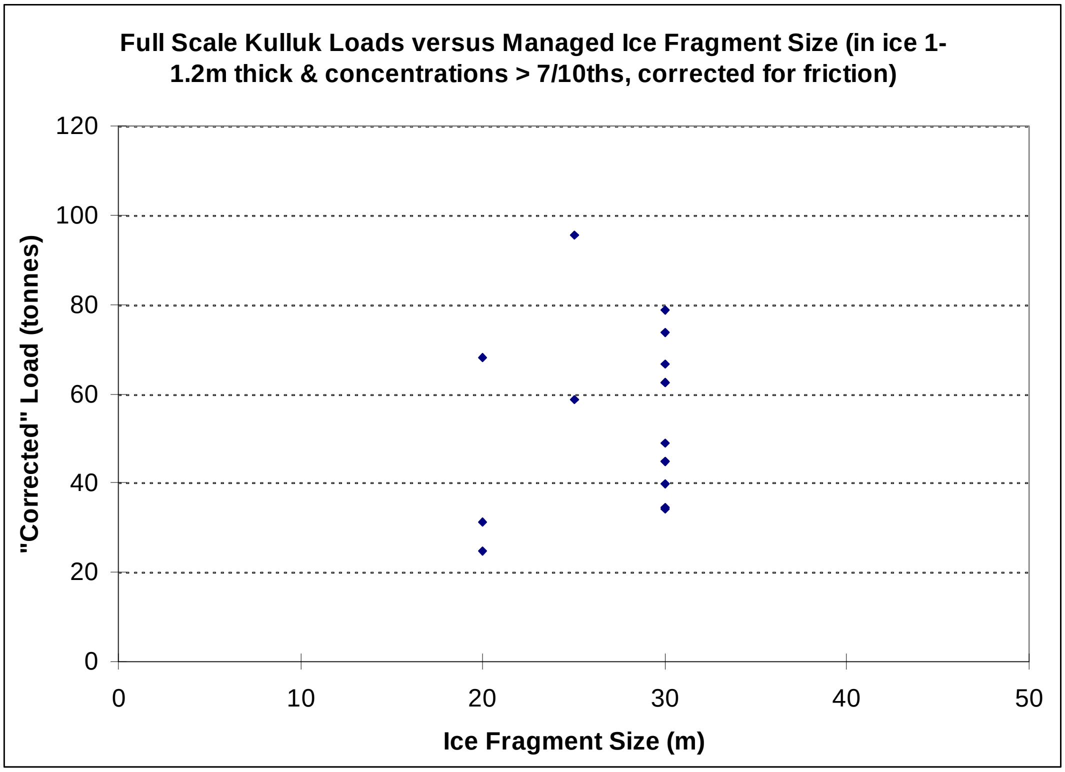

Full Scale Kulluk Loads in Managed Ice with Good Clearance vs Concentration
(in ice > 4m thick, corrected for friction at - 10C)
Corrected Load (tonnes)
0
50
100
150
200
250
300
350
400
0
1
2
3
4
5
6
7
8
9
10
Ice Concentration (10ths)

Figure 5.15


Full Scale Kulluk Loads versus Managed Ice Fragment Size (in ice 1-1.2m thick & concentrations > 7/10ths, corrected for friction)
"Corrected" Load (tonnes)
120
100
80
60
40
20
0
0
10
20
30
40
50
Ice Fragment Size (m)

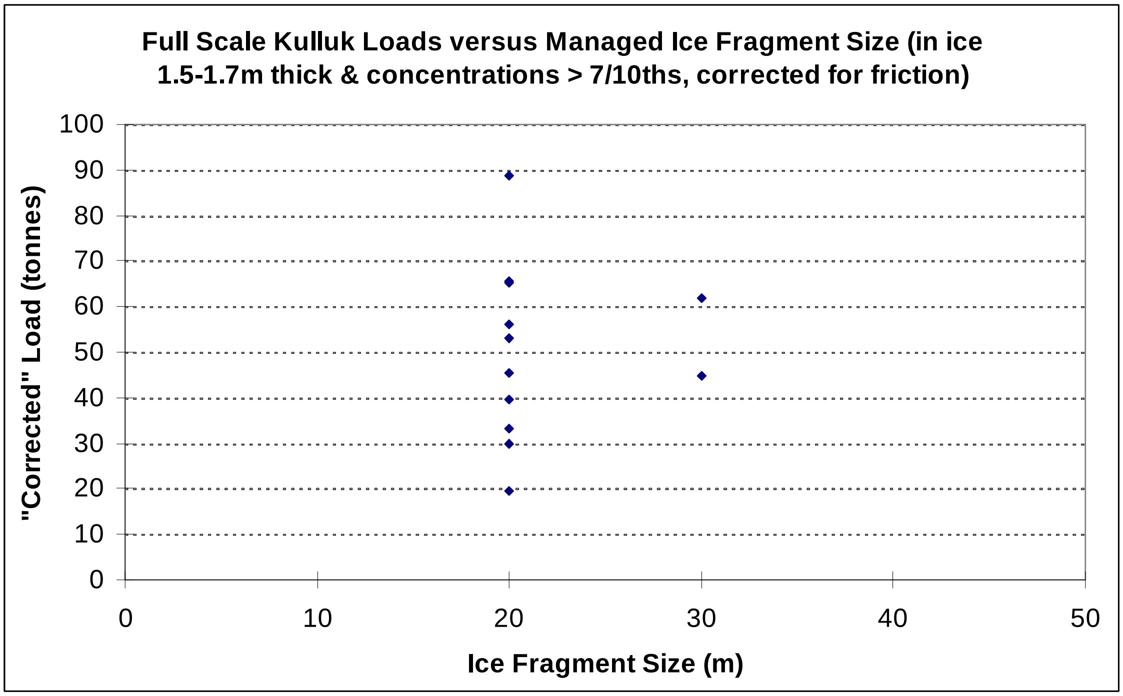
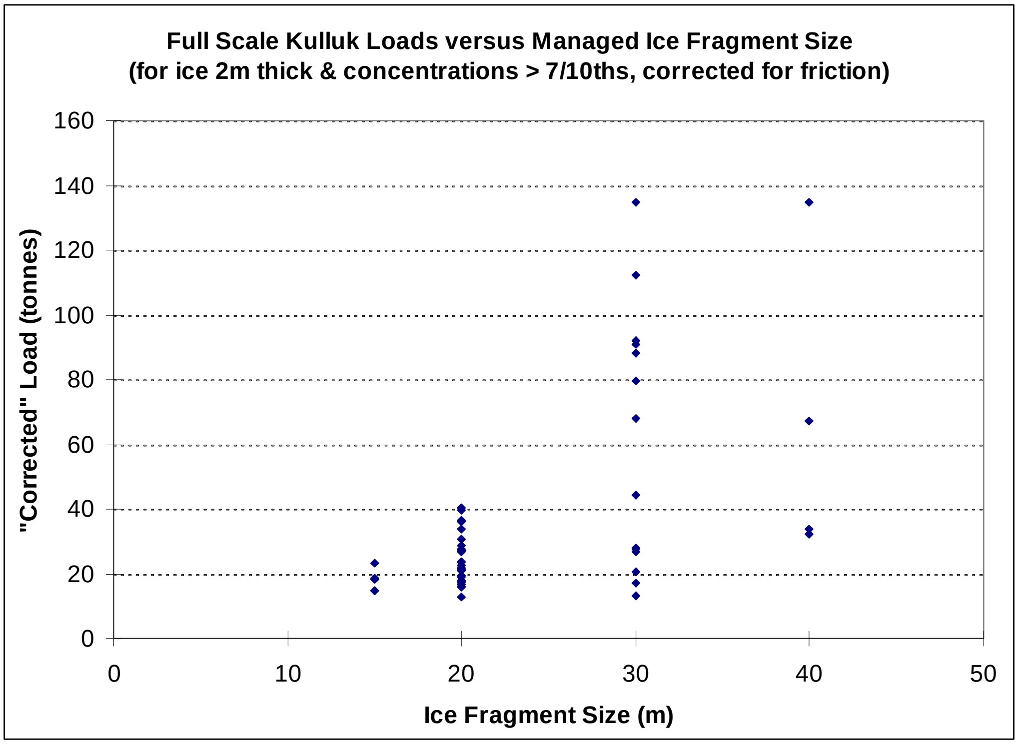

Full Scale Kulluk Loads versus Managed Ice Fragment Size (in ice 1.5-1.7m thick & concentrations > 7/10ths, corrected for friction)
"Corrected" Load (tonnes)
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
Ice Fragment Size (m)

Figure 5.16


Full Scale Kulluk Loads versus Managed Ice Fragment Size
(for ice 2m thick & concentrations > 7/10ths, corrected for friction)
"Corrected" Load (tonnes)
0
20
40
60
80
100
120
140
160
0
10
20
30
40
50
Ice Fragment Size (m)

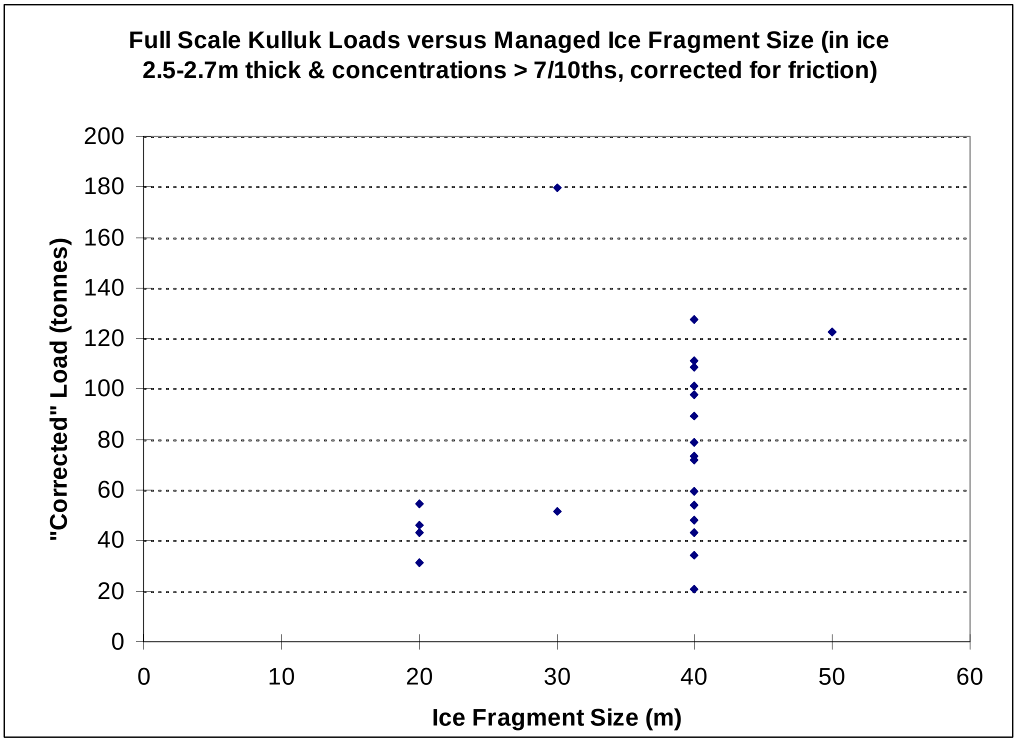
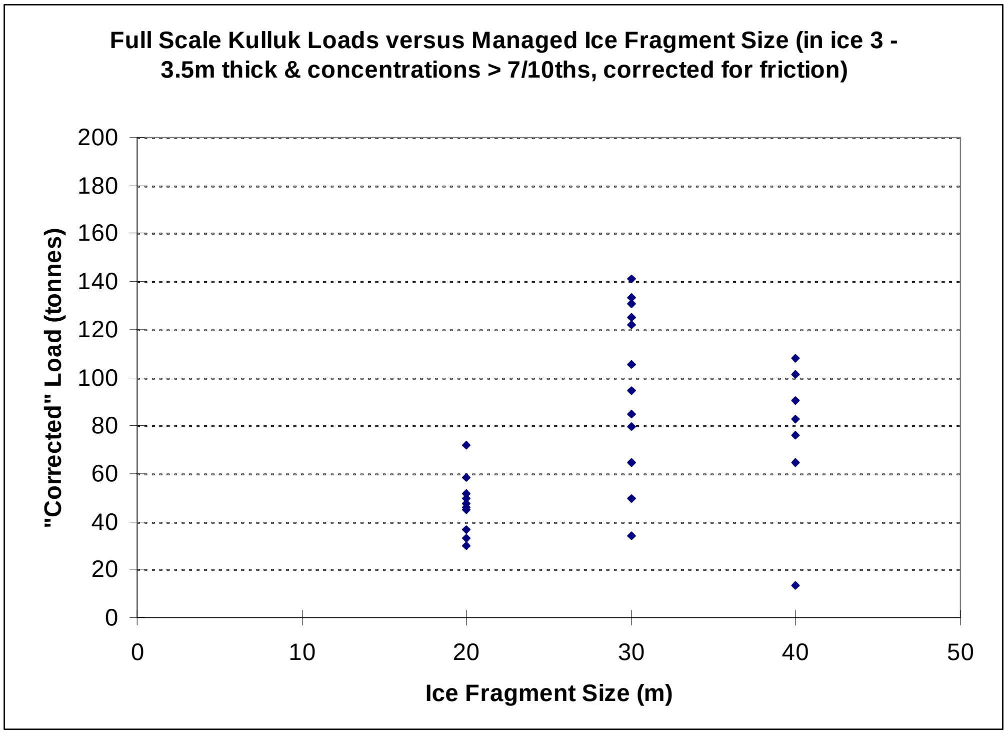

Full Scale Kulluk Loads versus Managed Ice Fragment Size (in ice 2.5-2.7m thick & concentrations > 7/10ths, corrected for friction)
"Corrected" Load (tonnes)
0
20
40
60
80
100
120
140
160
180
200
0
10
20
30
40
50
60
Ice Fragment Size (m)

Figure 5.17


Full Scale Kulluk Loads versus Managed Ice Fragment Size (in ice 3 - 3.5m thick & concentrations > 7/10ths, corrected for friction)
"Corrected" Load (tonnes)
0
20
40
60
80
100
120
140
160
180
200
0
10
20
30
40
50
Ice Fragment Size (m)

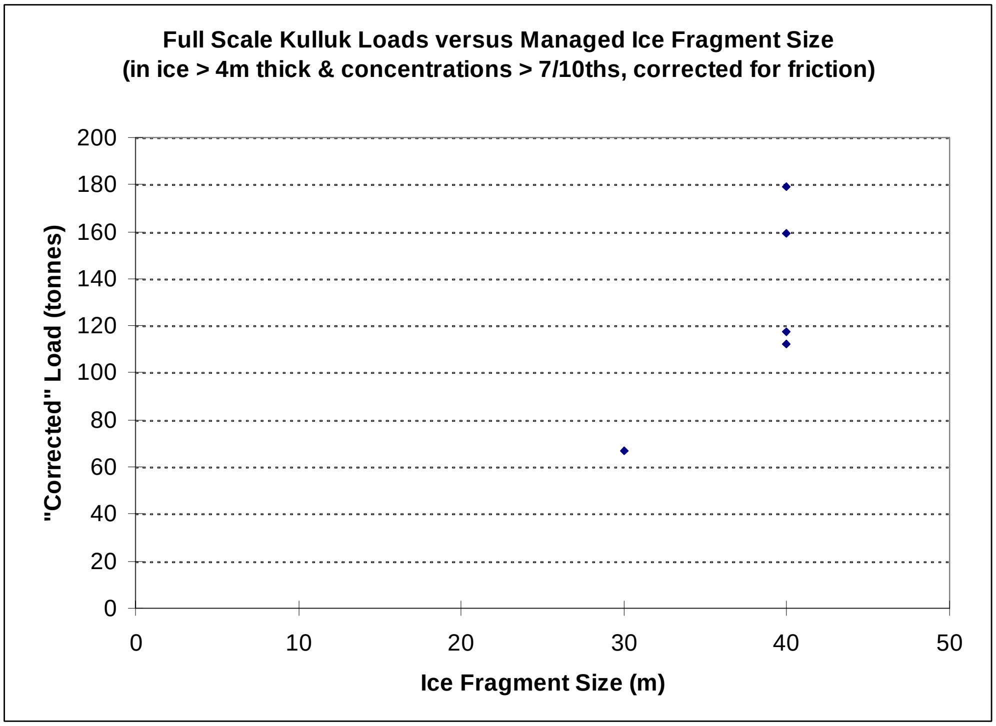

Full Scale Kulluk Loads versus Managed Ice Fragment Size
(in ice > 4m thick & concentrations > 7/10ths, corrected for friction)
"Corrected" Load (tonnes)
0
20
40
60
80
100
120
140
160
180
200
0
10
20
30
40
50
Ice Fragment Size (m)

Figure 5.18

5.2.4 Loads from Floe Impacts

The Kulluk data set contains a number of events that involved impacts with "discernable" ice floes or sizable managed ice floe fragments. These events were separated from the ones in well managed ice conditions with good clearance (ie: those discussed in Section 5.2.3), because the impacting floes were observed to be "somewhat different" from the general ice slurry moving past the vessel at the time. In short, the floes or floe fragments in this category were either quite large (≈75-150m in extent) or quite thick in comparison to the "average" managed ice condition. As an exception to the norm or "managed ice baseline", these events were specifically documented as floe impacts by the Kulluk's onboard staff..

It can be argued that in most cases, these floe impact events were simply the result of large floe fragments in a managed ice slurry, and should not produce loads that are very different from the characteristic load levels for this type of managed ice scenario. Recognizing this argument, the measured loads from these well documented floe impact events were plotted against the corresponding load levels seen in managed ice with good clearance, with the exception of the following three "extreme events".

- one involving a 500m diameter ice floe nearly 2.5m thick that impacted the Kulluk at 0.3 m/sec and produced a peak load of about 600 tonnes, before it rotated around the vessel

- one involving a heavily ridged old ice floe fragment about 200m in extent that moved against the Kulluk in a 9+/10ths heavy ice pressure situation, causing a peak load of nearly 300 tonnes before it rotated around the vessel

- one that was a "wake-up call" for many of the more adventuresome managers who were on the Kulluk and also overseeing the operation from onshore, that involved a very thick and heavily ridged old ice floe some 5 km x 8 km in extent impacting the Kulluk at 0.6 m/sec, driving the vessel off location, and quickly breaking some of the mooring lines in the process (despite the monumental stupidity of this incident, drilling activities had been suspended well prior to the impact event through the Kulluk's safety alert procedure)

The results are shown in Figure 5.19, where the loads measured during floe fragment impact events have been added to the load data given in the Figure 5.7 "slurry flow plot". It may be seen that these impact loads generally fall within the data scatter or towards its higher end. This suggests that the presence of floe fragments that are either slightly larger or thicker than the norm do not have a major impact on load levels in a managed ice slurry that clears well.

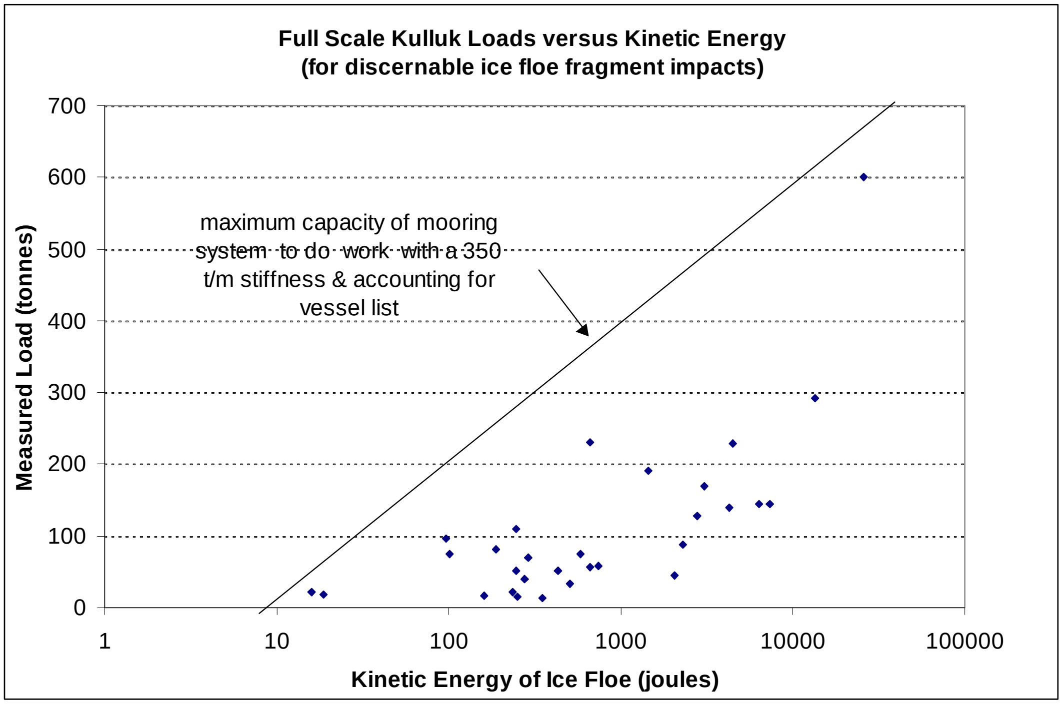


Figure 5.19

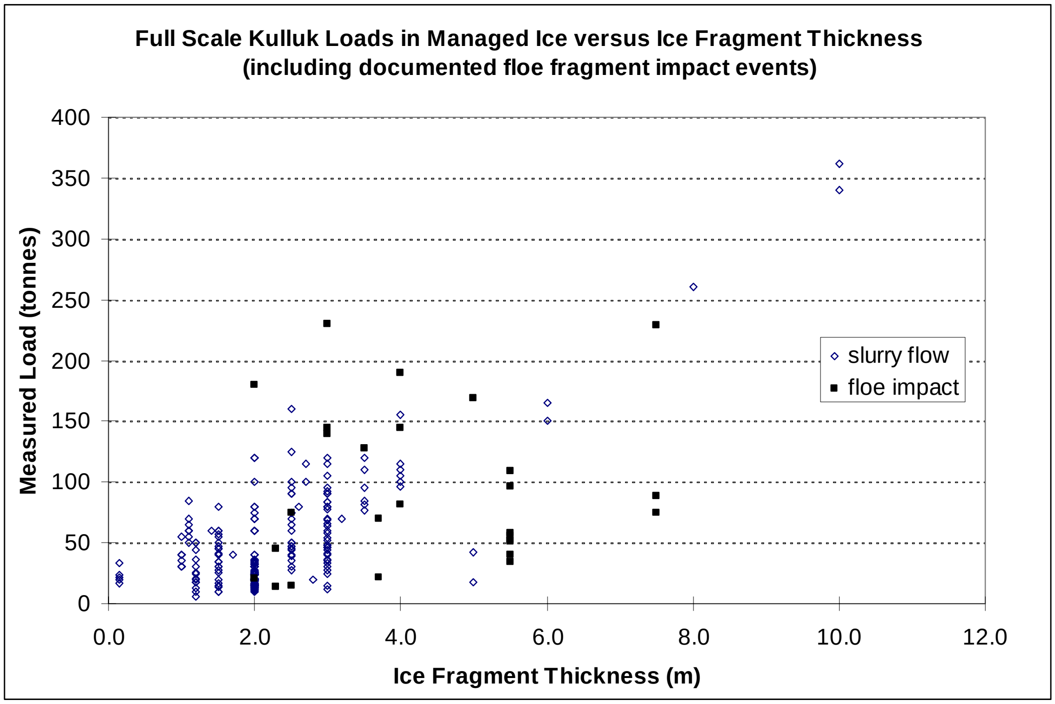


Figure 5.20

This well documented floe impact data has also been evaluated from an energy perspective. In Figure 5.20, the kinetic energy of each impacting floe or floe fragment has been plotted against the load that was measured during each event. The bounding line that is shown in this figure represents the capacity of the Kulluk to dissipate the kinetic energy of the floe impact, by doing work in its mooring system (with a system stiffness of 350 tonnes/m) and absorbing energy through the vessel's pitching motion. Although this plot is based on a straightforward analysis procedure and many simplifying assumptions (Gulf, 1985), it tends to support the following points.

- for moored vessels, there are a variety of energy sinks that can effectively dissipate the kinetic energy from most managed ice floe or thick fragment impacts, without large load levels being generated
- the use of basic physics provides a good means of estimating expected load levels for these types of fairly simple ice floe impact scenarios

5.2.5 Loads in "Tight" Managed Ice & in Pressure

The Kulluk data set contains a large number of loading events in managed ice conditions, when the ice floe fragments that were produced through the ice management process did not clear easily around the vessel., due to the particulars of the ice conditions that were present at the time. There are also a variety of data set entries that cover situations when the Kulluk experienced ice pressure, which challenged the performance of its ice management vessels and generally caused higher load levels. The types of ice interactions that were observed during these loading events were quite different to what has been referred to here as "good clearance or slurry flow" conditions.

In "tight" ice situations that involved pack ice concentrations in excess of 9/10ths with "some lateral restraint", managed ice floe fragments tended to accumulate updrift of the Kulluk in the form of a floating rubble wedge. Figure 5.21 provides an illustration of this type of ice interaction behaviour, resulting from "tight ice" and poor clearance conditions. These events were not particularly frequent compared to those involving good ice clearance. However, they did produce a significant number of loading events. The measured load data that is associated with this type of "poor ice clearance" scenario is shown in Figure 5.22. It is clear that there is a general trend towards increasing load levels with increasing ice thicknesses. Ice concentration influences are not particularly relevant, because all of these events occurred in concentrations of 9 to 9+/10ths. The effect of ice drift speed and managed ice piece size, although not shown here, is not significant across the range of ice conditions encountered.

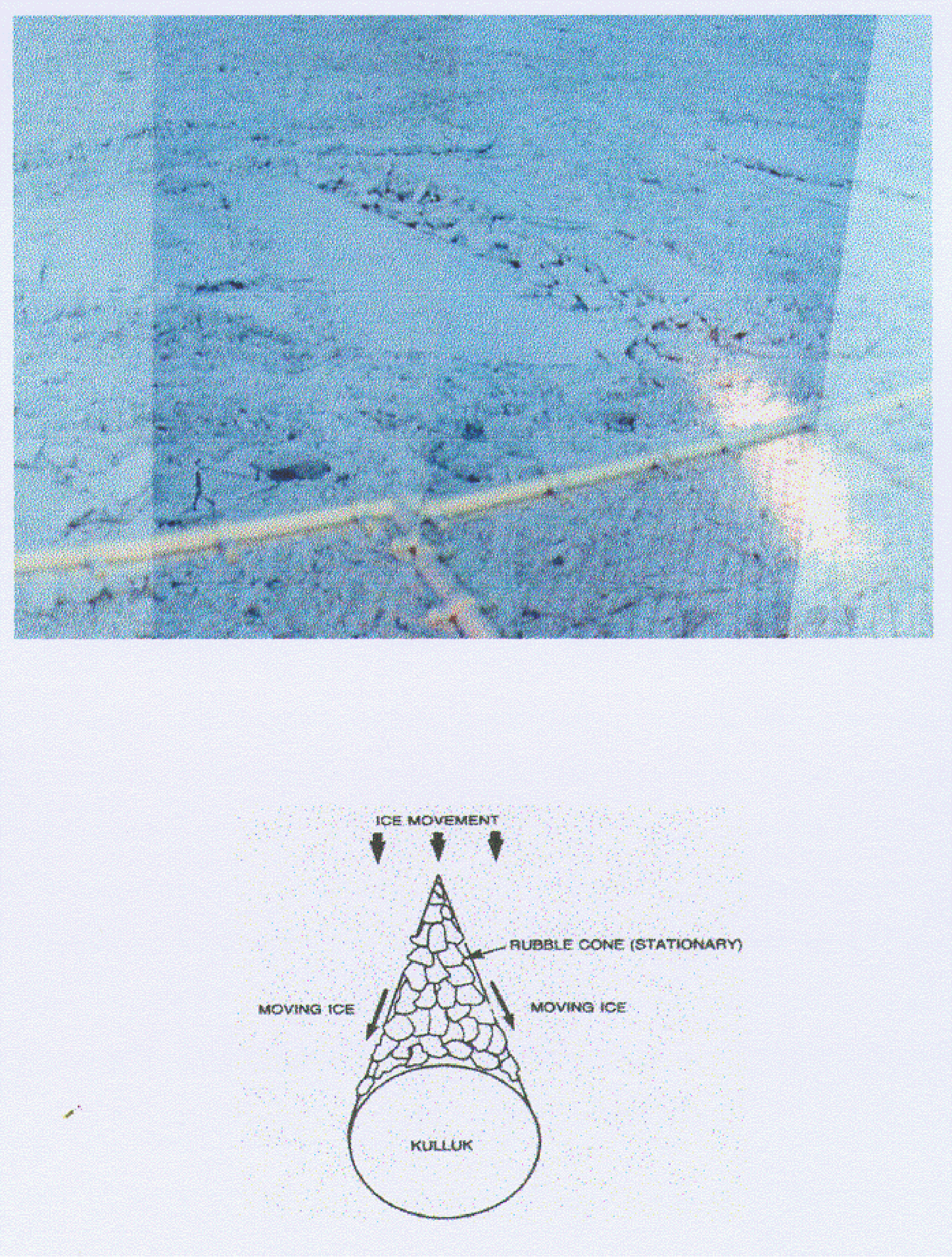


Figure 5.21 The upper photo provides a representative example of poor ice clearance in "tight" pack ice conditions around the Kulluk. In this situation, the managed ice fragments are not clearing well, and a "rubble wedge" can be seen updrift of the Kulluk. The lower figure is a schematic illustration of this situation.

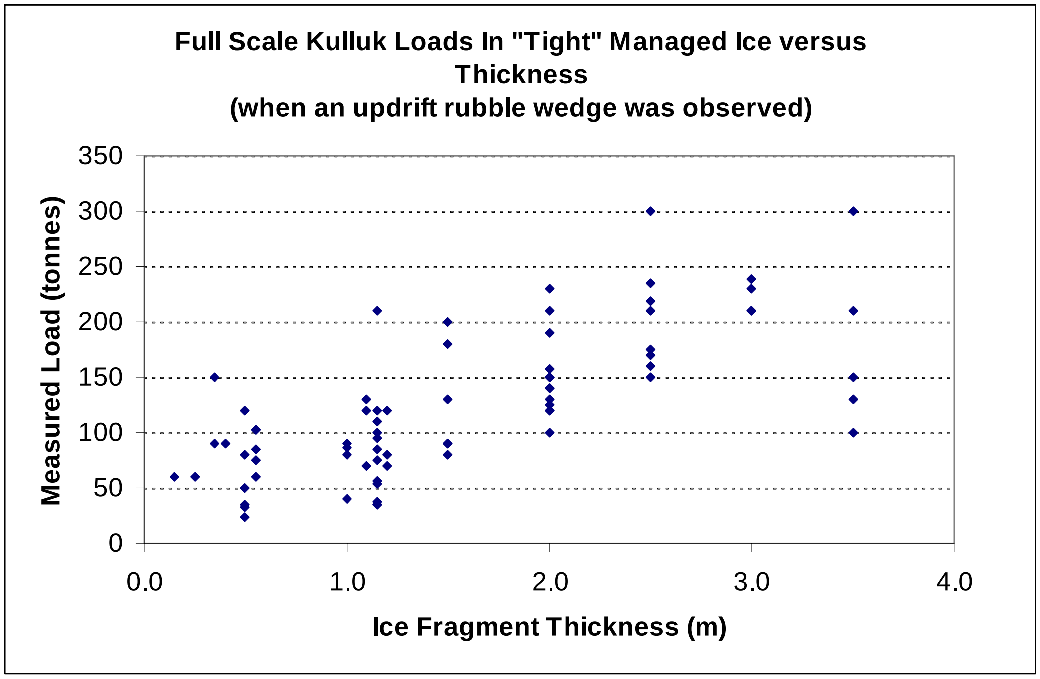


Figure 5.22

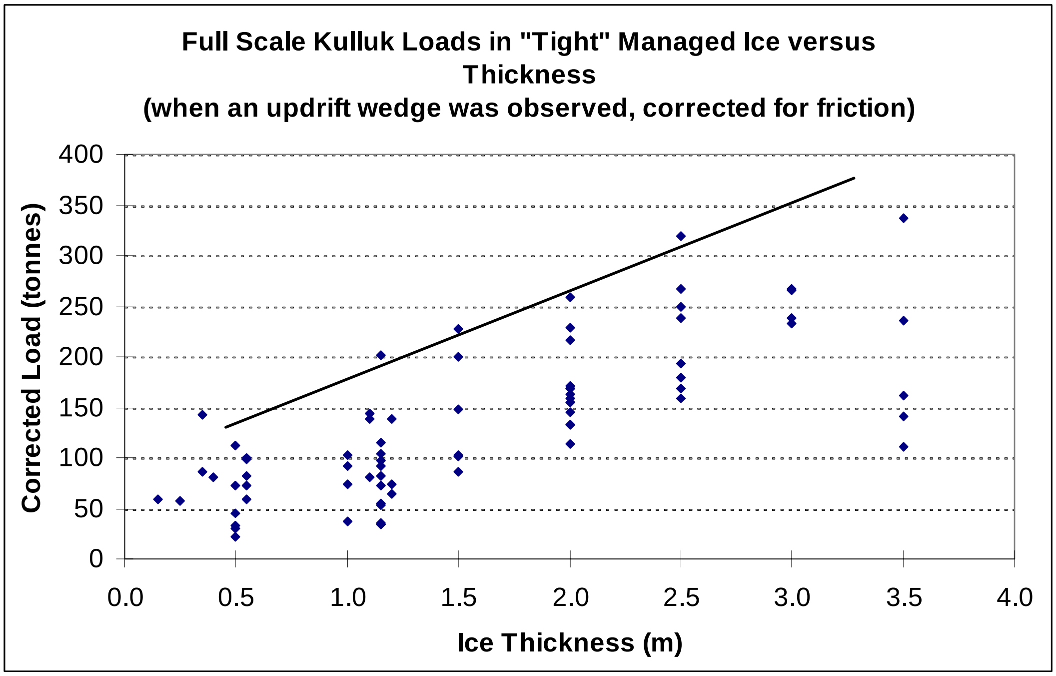


Figure 5.23 The upper bound line to these loads in tight managed ice conditions, with poor ice clearance and an updrift rubble wedge, is described by y = 87 x + 91.

Figure 5.23 shows the same load data, normalized for variable frictional effects and bounded, according to the procedures outlined earlier. The main points that should be made on the basis of this plot are given as follows:

- the load levels that can be experienced in managed ice conditions with poor clearance are generally higher than those in managed ice with good clearance, by up to a factor of two
- despite this increase, poor ice clearance in managed ice conditions still results in much lower load levels than in unmanaged ice, particularly when thick rough ice areas are involved

There are a variety of events in the data set when significant ice pressure was experienced. These situations also resulted in an updrift rubble wedge against the Kulluk, but with "more confined ice action" along the boundaries of the wedge, often combined with local rafting and ridging. The load data that is associated with the more significant ice pressure events is shown in Figure 5.24, overlain on the previous plot. It can be seen that the loading events involving significant ice pressure typically produced load levels that were substantially higher than those in tight managed ice conditions, by a factor of about two. It is noteworthy that some of the loads measured in significant ice pressure situations are in the same range or higher than those experienced in unmanaged ice conditions, for similar ice thicknesses.

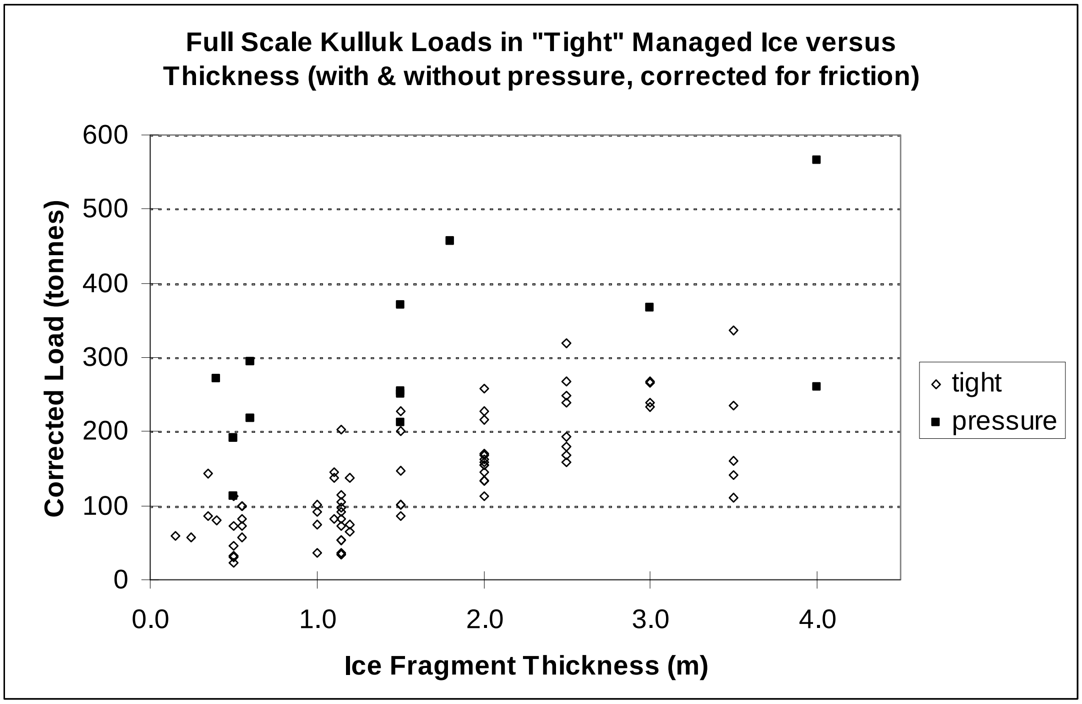


Figure 5.24

In the context of Grand Banks developments, these types of “tight or pressured” ice loading situations should not be of much concern, because 9 to 9+/10ths ice conditions are rarely encountered in the region and significant ice pressure events are virtually unheard of.

5.2.6 Nature of Loads

Many of the load event entries in the Kulluk data set contain information about the nature of the ice loads that were experienced in a particular situation. Clearly, measures such as the rise time for a loading event, the ratio of the peak to the “typical load level” seen at the onset of the event, and the duration of the event are all important factors. This type of information can be used to obtain some perspectives in relation to the following questions.

- how quickly can high loads come on ?
- can load peaks be significantly higher than “baseline load levels” and catch a moored vessel stationkeeping operation “unaware” ?
- are high loading events relatively short or fairly long in duration ?

Here, information pertaining to load event rise times, peak to mean load ratios, and load event durations has been extracted from the full scale Kulluk data set, on a scenario by scenario basis. The three types of ice interaction situations that have been considered include:

- those involving managed ice conditions with good clearance
- those involving tight ice conditions and an updrift rubble wedge
- those involving the occurrence of ice pressure

The basic source of this information is the global load time series records that were acquired onboard the Kulluk in real time. Representative examples of these load traces which show the nature of some of the loading events that the Kulluk experienced are given in Figures 5.25 to 5.27, for the three ice interaction scenarios noted above. In Figures 5.28 to 5.30, composite information about the nature of many of the Kulluk loading events is provided in the form of cumulative exceedence distributions for load rise times, peak to mean load ratios and load event durations, again on a scenario by scenario basis.

The main points that should be made on the basis of these figures are as follows..

- the time dependent nature of any loading event is related to the ice and ice clearance conditions that are present at the time (and any ice management technique that may be used to “relieve’ the situation)

- managed ice with good ice clearance usually produces the most “quiescent” loading situation, for example:

  - load rise times are typically in the range of tens of seconds to several minutes
  - peak to mean load ratios are relatively small, in the range of 2 and less
  - load events are usually short lived, with typical durations of a few minutes

- tight managed ice situations with poor ice clearance, and those involving ice pressure, are more "uncertain" loading situations, for example:

  - load rise times typically range of about 10 minutes to an hour or more
  - however, peak to mean load ratios can be quite high, in the range of 2.5 to 4
  - load event durations can last from tens of minutes to a few hours (or more)

This information is intended to provide "some feel" for many of the loading events that the Kulluk experienced. However, the nature of any particular loading event was usually unique, and was related to the specifics of the ice and ice management situation present at the time.

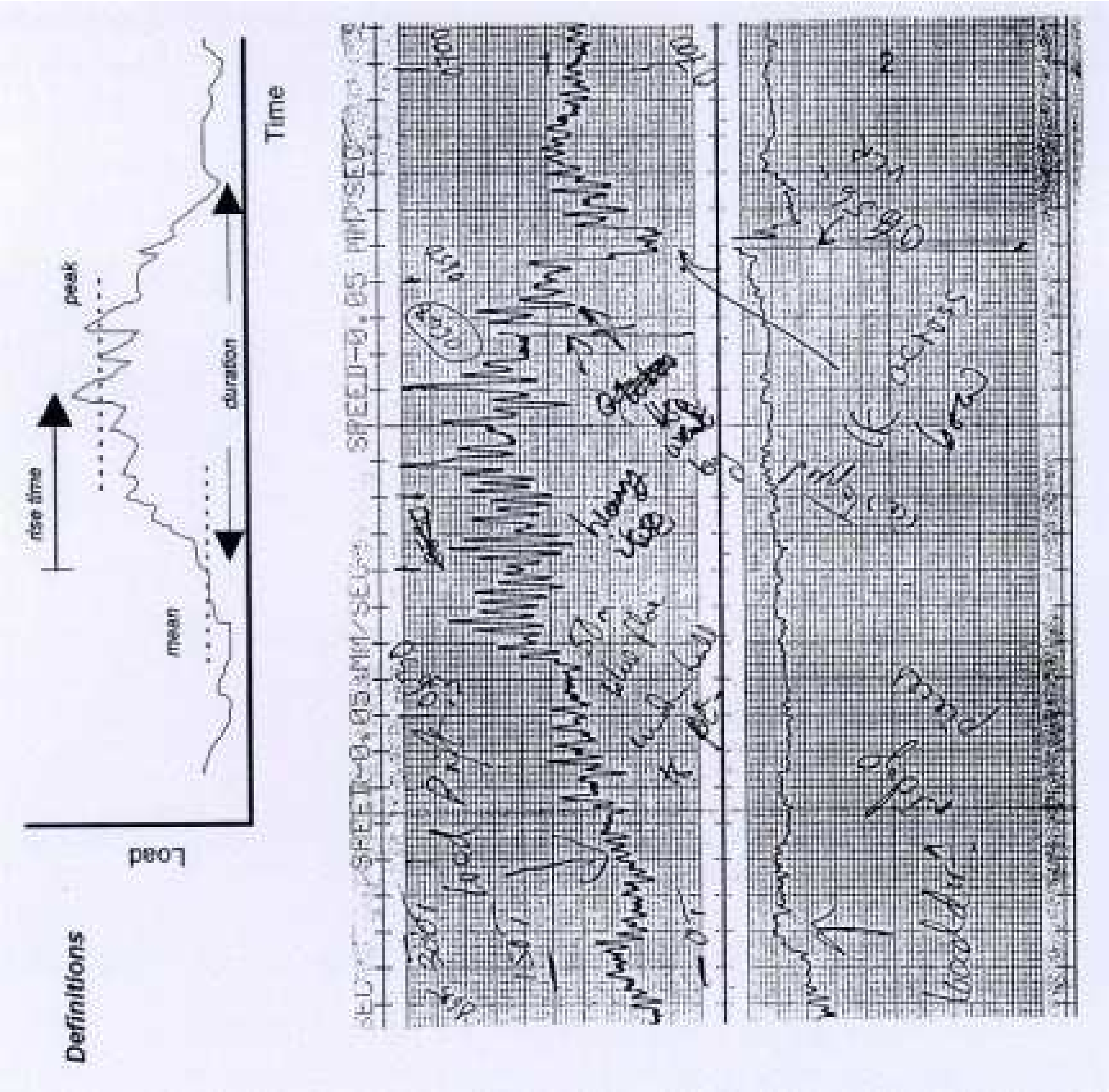


Figure 5.25 Typical "global load" time series for the Kulluk (from the original strip chart records), in managed ice conditions with good ice clearance.

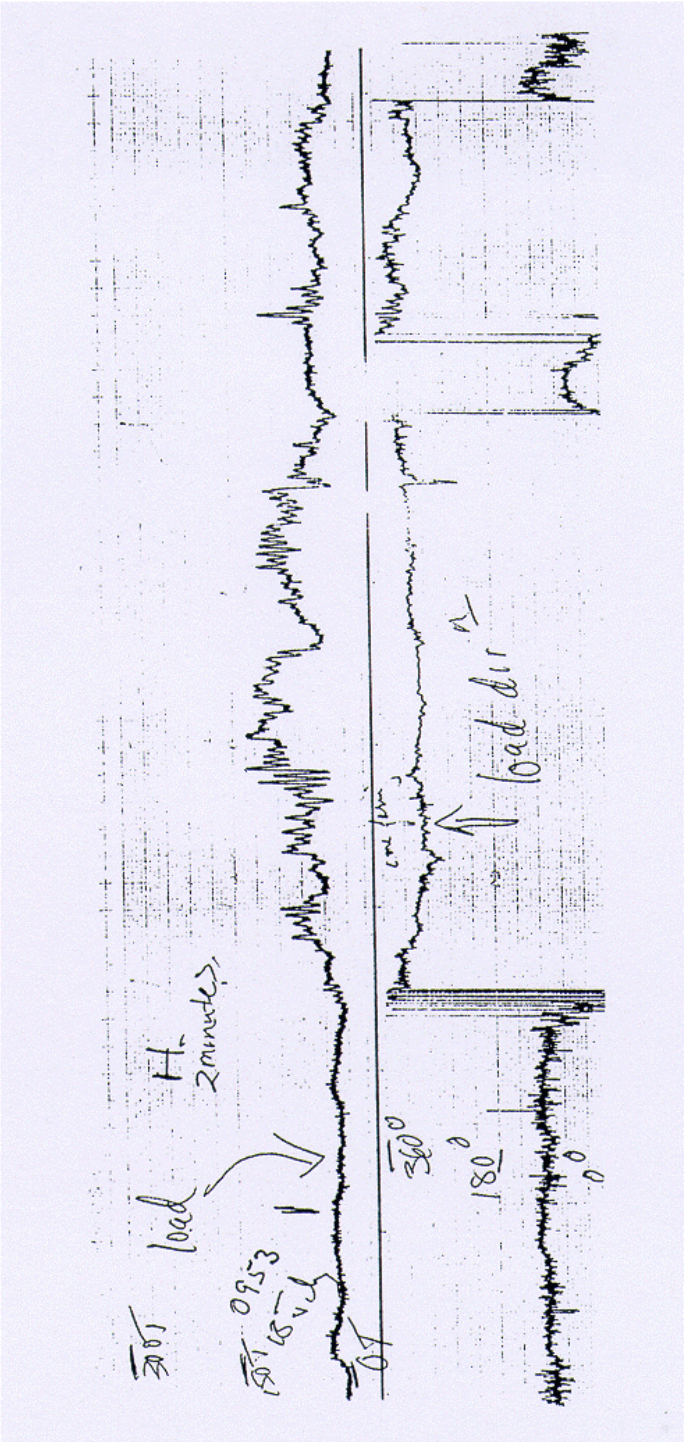


Figure 5.26 Typical "global load" time series for the Kulluk (from the original strip chart records), in tight managed ice conditions with poor clearance and an updrift rubble wedge.

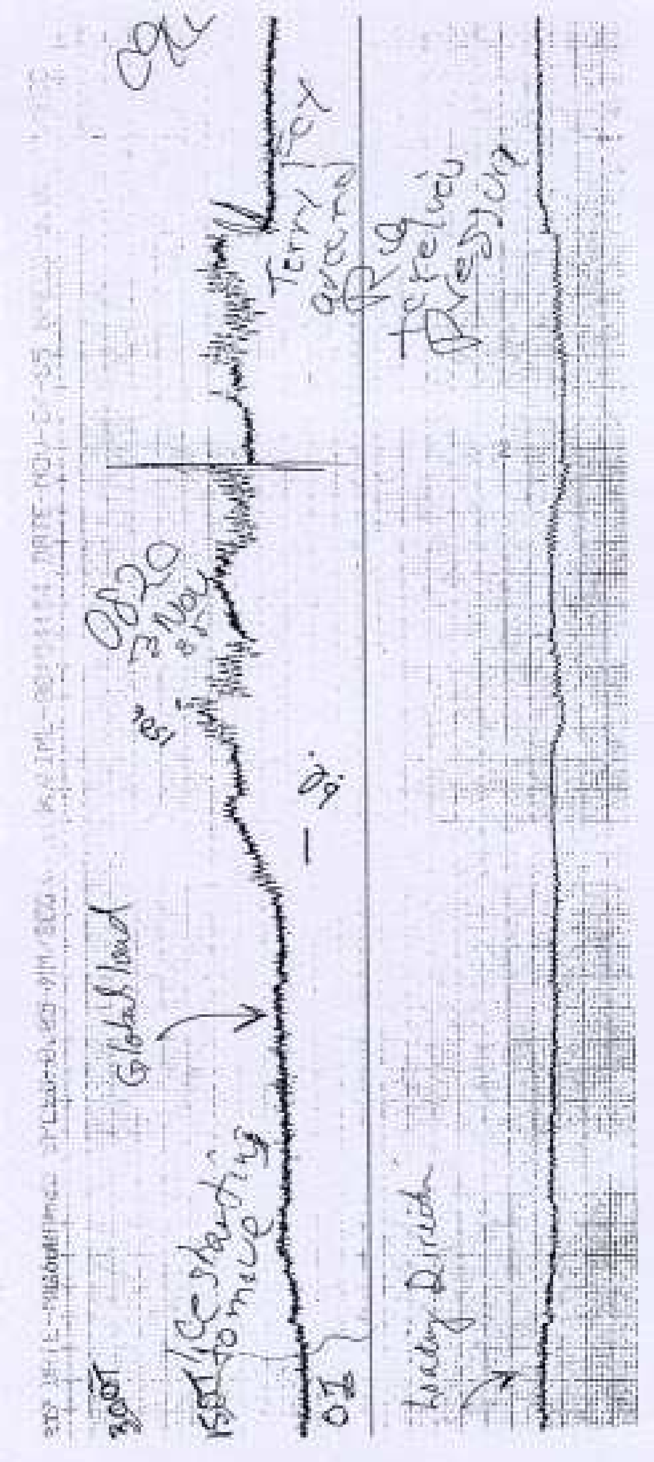
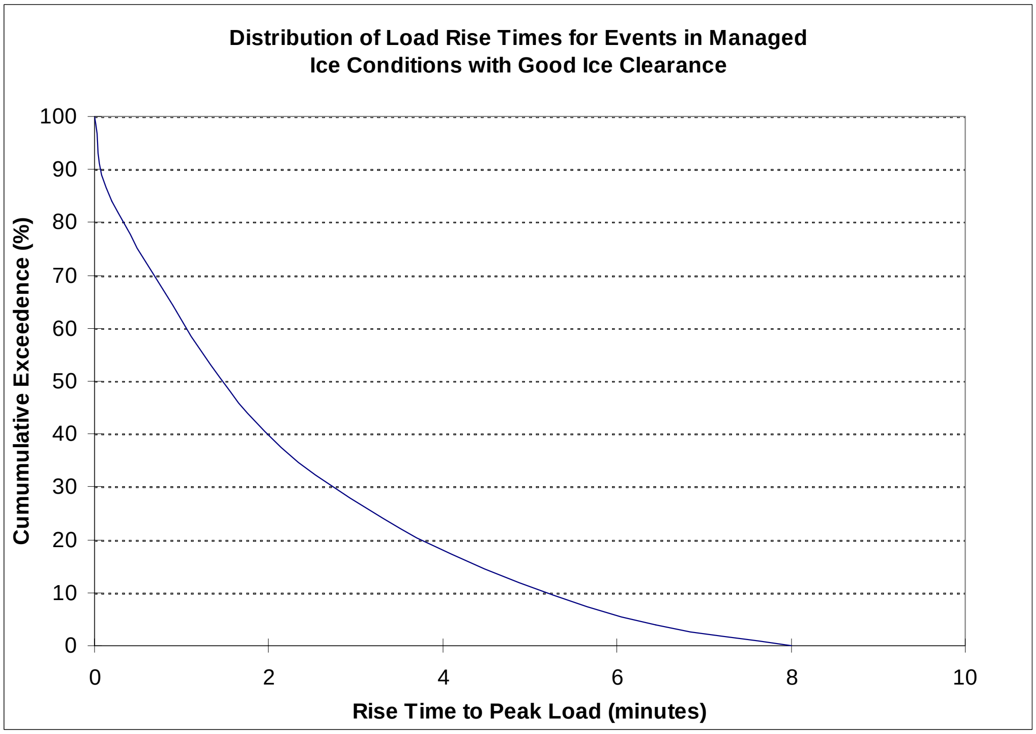


Figure 5.27 Typical "global load" time series for the Kulluk (from the original strip chart records), in managed ice conditions with poor clearance under pressure.


Distribution of Load Rise Times for Events in Managed Ice Conditions with Good Ice Clearance
Cumumulative Exceedence (%)
100
90
80
70
60
50
40
30
20
10
0
0
2
4
6
8
10
Rise Time to Peak Load (minutes)

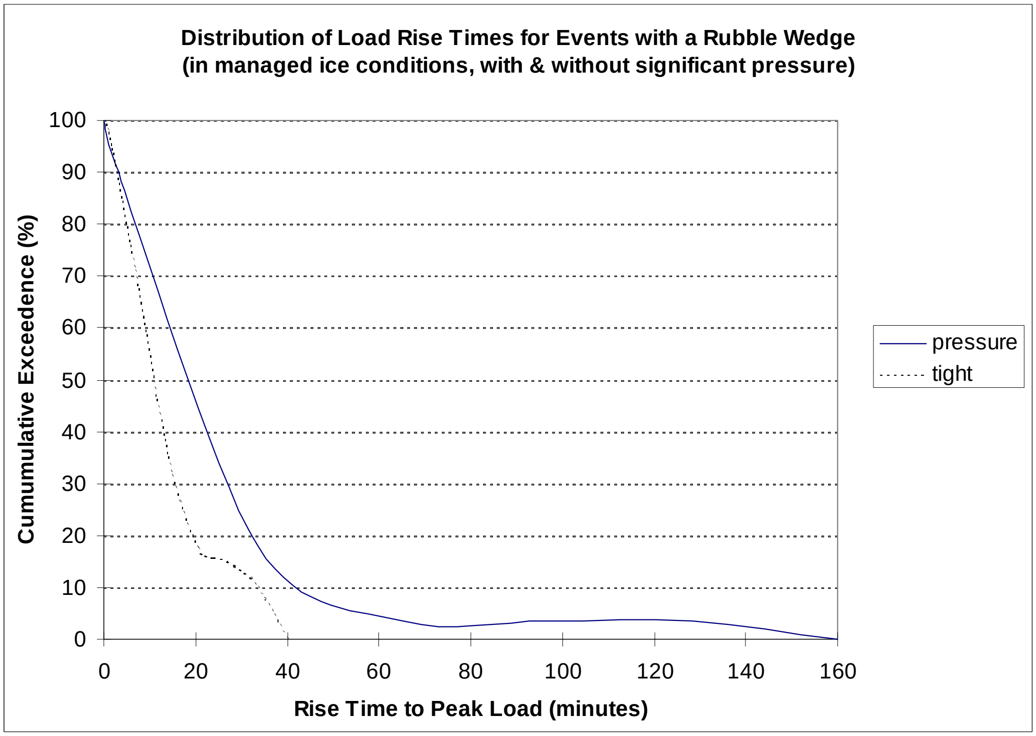
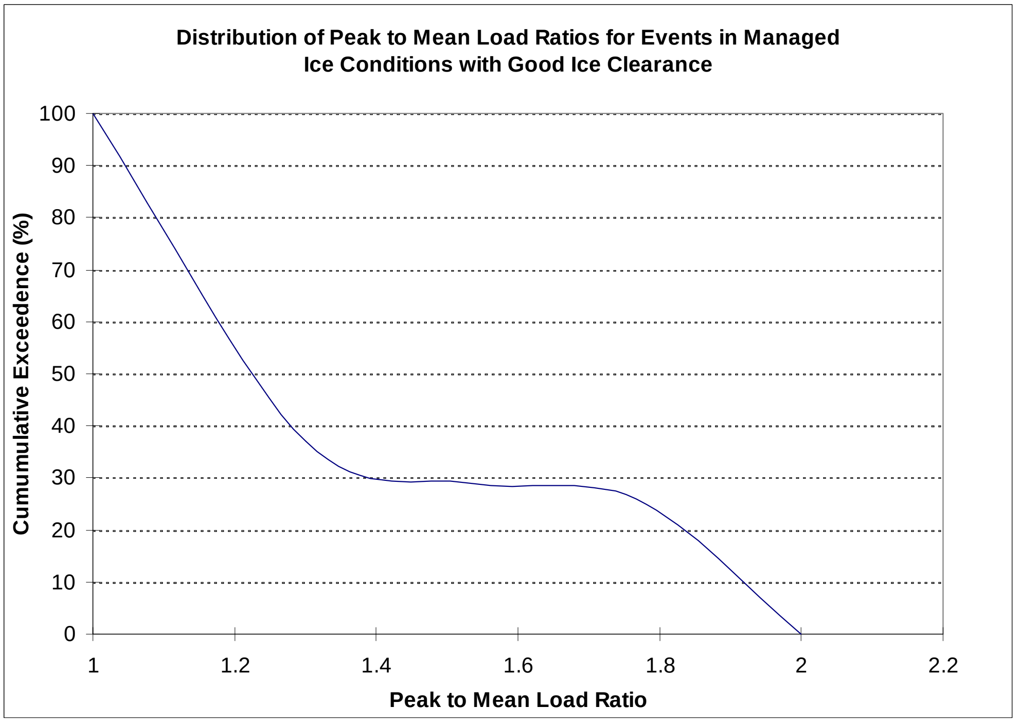

Distribution of Load Rise Times for Events with a Rubble Wedge (in managed ice conditions, with & without significant pressure)
Cumumulative Exceedence (%)
100
90
80
70
60
50
40
30
20
10
0
0
20
40
60
80
100
120
140
160
Rise Time to Peak Load (minutes)
pressure
tight

Figure 5.28


Distribution of Peak to Mean Load Ratios for Events in Managed Ice Conditions with Good Ice Clearance
Cumumulative Exceedence (%)
100
90
80
70
60
50
40
30
20
10
0
1
1.2
1.4
1.6
1.8
2
2.2
Peak to Mean Load Ratio

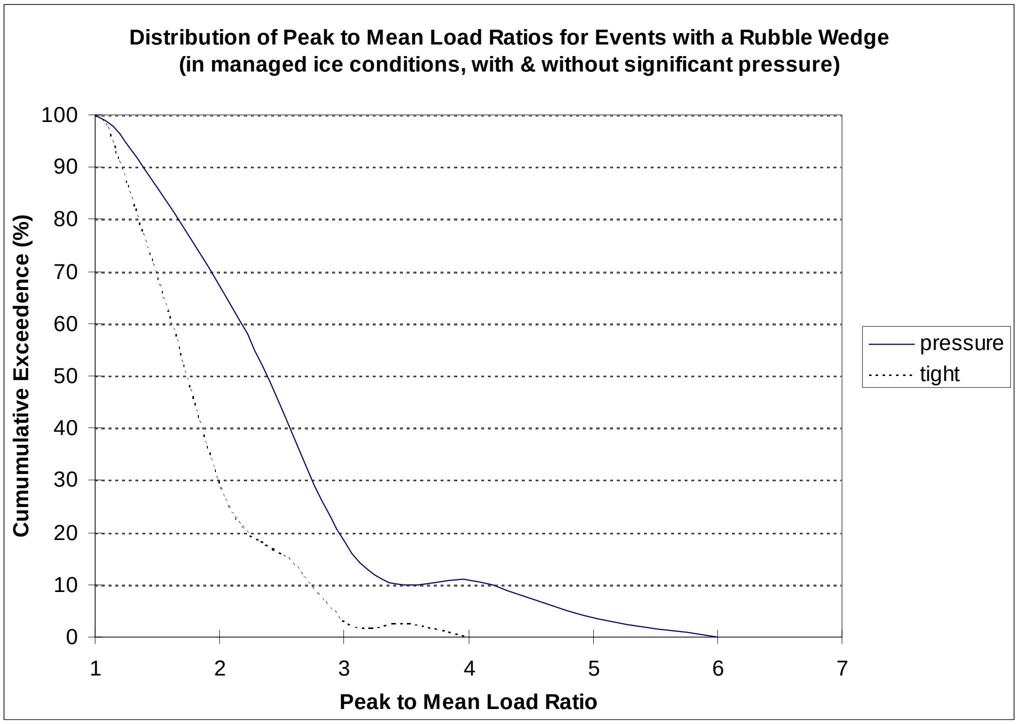
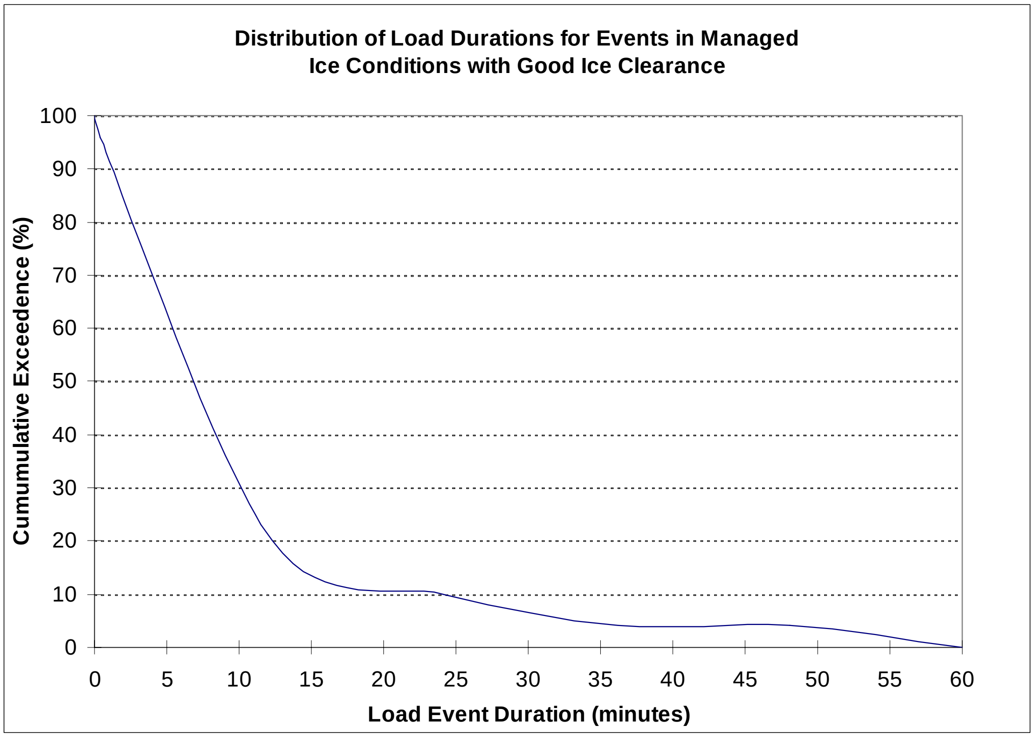

Distribution of Peak to Mean Load Ratios for Events with a Rubble Wedge (in managed ice conditions, with & without significant pressure)
Cumumulative Exceedence (%)
100
90
80
70
60
50
40
30
20
10
0
1
2
3
4
5
6
7
Peak to Mean Load Ratio
pressure
tight

Figure 5.29


Distribution of Load Durations for Events in Managed Ice Conditions with Good Ice Clearance
Cumumulative Exceedence (%)
0
10
20
30
40
50
60
70
80
90
100
0
5
10
15
20
25
30
35
40
45
50
55
60
Load Event Duration (minutes)

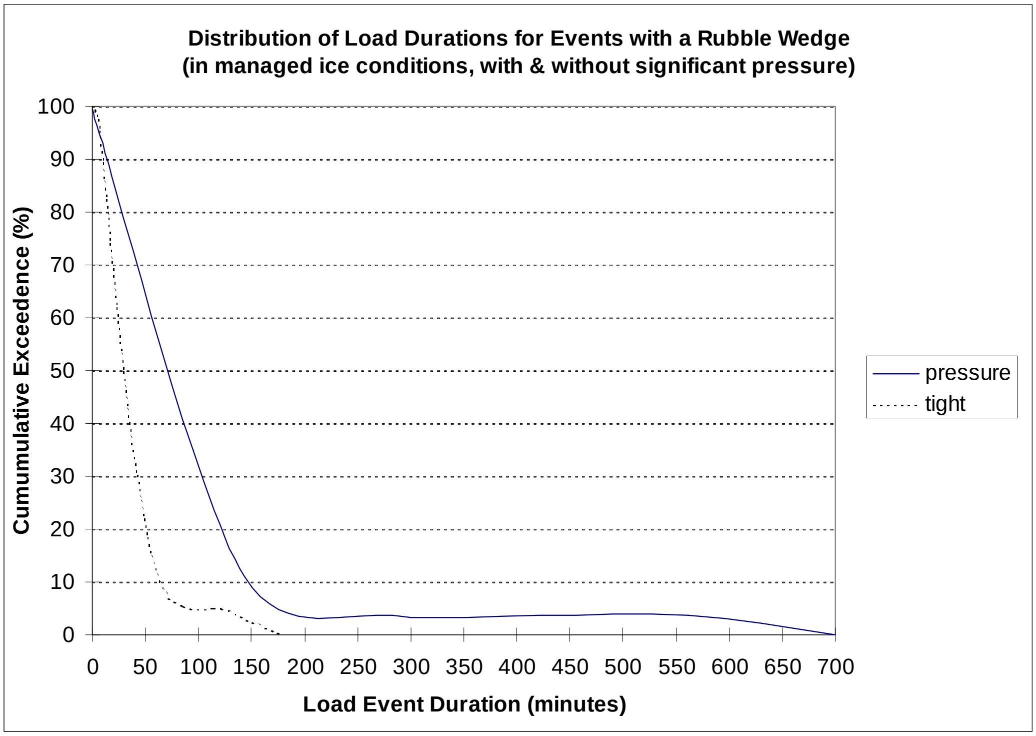

Distribution of Load Durations for Events with a Rubble Wedge (in managed ice conditions, with & without significant pressure)
Cumumulative Exceedence (%)
0
10
20
30
40
50
60
70
80
90
100
0
50
100
150
200
250
300
350
400
450
500
550
600
650
700
Load Event Duration (minutes)
pressure
tight

Figure 5.30

5.3 Ship Data

Because of its unique design, there is a common perception that the Kulluk was “completely different” than any other vessel, and that the load levels it experienced in moving pack ice conditions bear little relevance to what should be expected on a “normal” moored vessel. In this section, the load data that was obtained from icebreaker performance trials and other ship operating events is compared to the Kulluk load information. The purpose of this comparison is to assess whether or not these different full scale data sources actually fit together in a sensible manner and form a fairly consistent pattern.

5.3.1 Data Standardization

The full scale vessel trials and operations information that is contained in the ship component of the data set involves differently sized and shaped vessels, and a wide range of different ice conditions. In order to make sensible intercomparisons, this data must be “corrected or standardized” to a common vessel form and similar set of ice conditions. 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 vessel dimensions, hull form, hull surface conditions, ice strengths and ambient temperatures. These parametric dependencies, which have been used as a basis for standardizing the full scale ship data to the Kulluk’s size and hull form in this work, are given as follows.

Ship resistance in ice is proportional to:

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

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

It should be noted that these parametric dependencies are strictly applicable at a speed of 1m/s. However, the speed range of interest in this work is small, and the speed influence on resistance is also relatively small. Therefore, these dependencies have been used for a first level correction. Moreover, the parametric dependencies are also strictly applicable to level ice resistance, which would generally include a higher proportional influence of icebreaking parameters such as ice strength than broken or managed ice resistance. However, with no justification for making quantitative modifications, the original dependencies have been used as is. The validity of the corrections will be judged pragmatically, by the level to which they tend to bring all of the data into some logical order.

On the basis of the parametric dependencies given above, the ship resistance data in broken ice channels and the loads from other in-ice ship operations (ie: Canmar's JIP events) have been corrected to one common vessel design, namely the Kulluk. The Kulluk has been treated as a vessel with the following parameter values.

C_S = 1.0 for saline ice

C_h = 1.0 for low friction coating .
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
σ_f = 500 kPa flexural ice strength
T = -10 °C ice surface or air temperature

The corresponding parameter values for all of the ships for which there is full scale load or resistance data are given in the data set. These values have been used on a case by case basis in the data standardization procedure. An example of this process is given in Appendix 3.

5.3.2 Load Intercomparisons

Ship Trials Data

The original channel resistance data for the eight icebreakers is given in Figure 5.31 and the data, adjusted to "standard Kulluk design and ice conditions", is shown in Figure 5.32. It can be seen that the wide spread of ship resistance results, because of vessel size, hull form and ice condition differences, has been adjusted to a data set that shows some logical order.

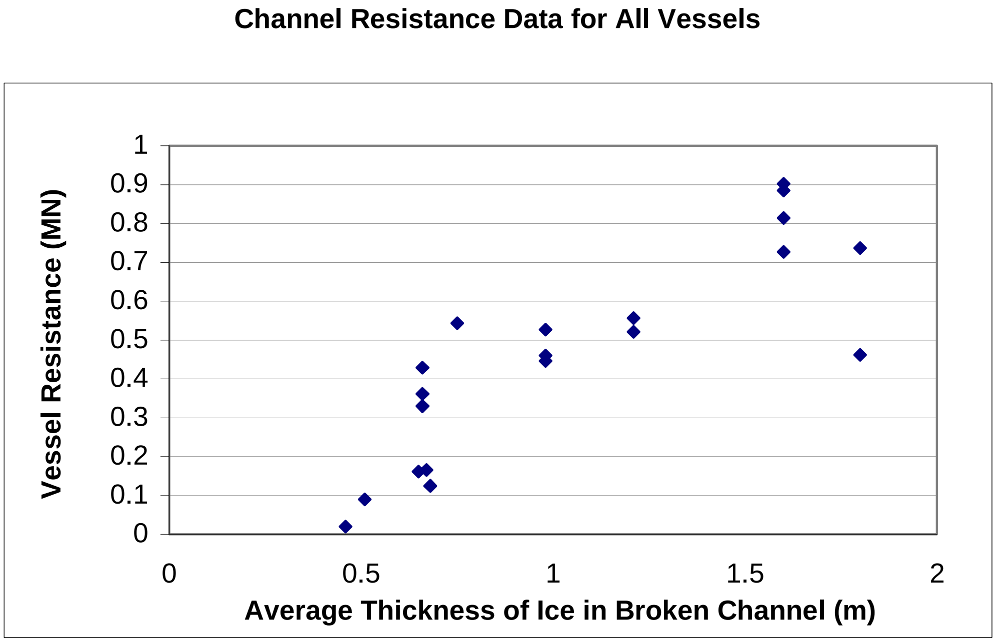


Figure 5.31 **Original ship trials resistance data in broken ice channels, uncorrected for vessel size and form**

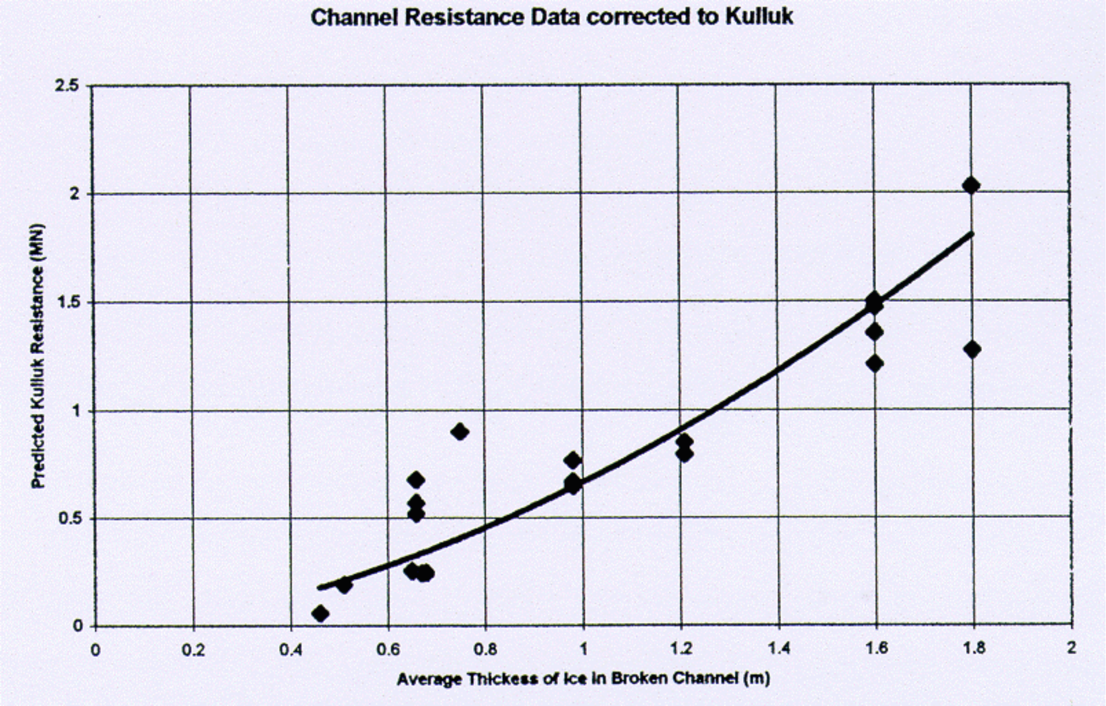


Figure 5.32 **Ship trials resistance data in broken ice channels, corrected to the Kulluk's size and hull form.**

This slow speed resistance data reflects fairly steady load levels on vessels in a broken level ice channel, with close to 10/10ths coverage and having a measure of restriction on lateral clearing. In a 1m ice thickness, the resistance (corrected to the Kulluk's hull size an shape) is about 70 tonnes and appears to increase with ice thickness, a little more than linearly.

In Figure 5.33, these twenty data points from ship trials in broken ice channels, standardized to the Kulluk's hull form, are directly compared with the Kulluk load data in tight managed ice conditions. Here, the bounding lines for "tight ice" and "good ice clearance or slurry flow" conditions are both shown for reference. Error bars of +/- 50% have been placed on the ship data points, to reflect the fact that they represent mean resistance rather than peak load values and to accommodate uncertainties in the "ship to Kulluk" data standardization procedure. The level of agreement that can be seen between the two data sets is actually quite remarkable

Ship Operating Events

The load estimates for the high quality in-ice ship operating events that were extracted from Canmar's JIP study were also adjusted to the dimensions and shape of Kulluk, then plotted against relevant Kulluk load data. These intercomparisons are highlighted as follows.

- in addition to the broken channel resistance data, Figure 5.33 contains two loading points from Canmar's JIP that involved ship events in tight managed ice conditions. The load levels that are indicated by these two data points, corrected to the Kulluk's hull form, are in good agreement with the Kulluk data.

- Figure 5.34 shows four other loading events from Canmar's JIP that involved ships in pressured ice conditions. Although there is considerable scatter in both the JIP and Kulluk data points, there is reasonably good agreement between the two data sets.

- Figure 5.35 is perhaps the most surprising of all. This figure shows the loading events from Canmar's JIP, where they were interpreted in terms of an equivalent level ice thickness, plotted against the Kulluk load data in level unbroken ice. Again, the two data sets are in very good agreement.

The fact that the load and resistance data from various ship trials and other in-ice operating events relates to the Kulluk load data so well is extremely encouraging. It suggests that all of the full scale data covered in this report ties together sensibly, and provides a consistent and credible basis for reasonably estimating expected load levels on moored vessels in a variety of moving pack ice conditions, with some confidence.

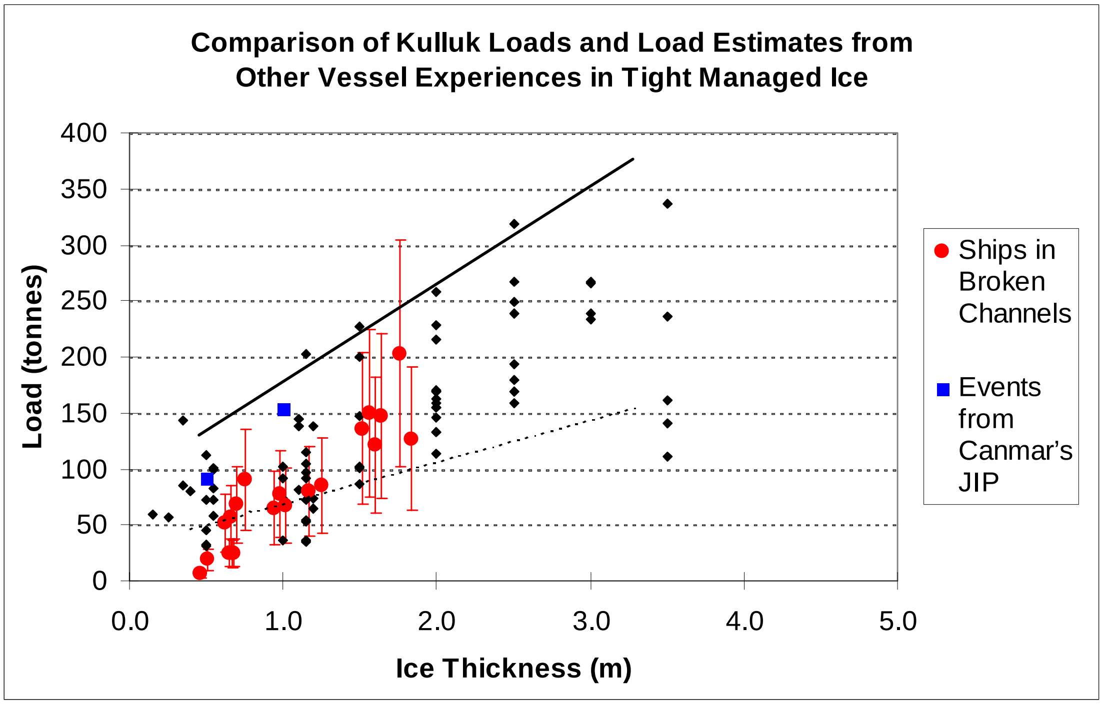


Figure 5.33 **The upper and lower bound lines that are shown are for the full scale Kulluk load data in managed ice, with poor and good ice clearance, respectively. The broken channel ship resistance data should be expected to fall between these two lines, because of the type of ice clearance scenario involved.**

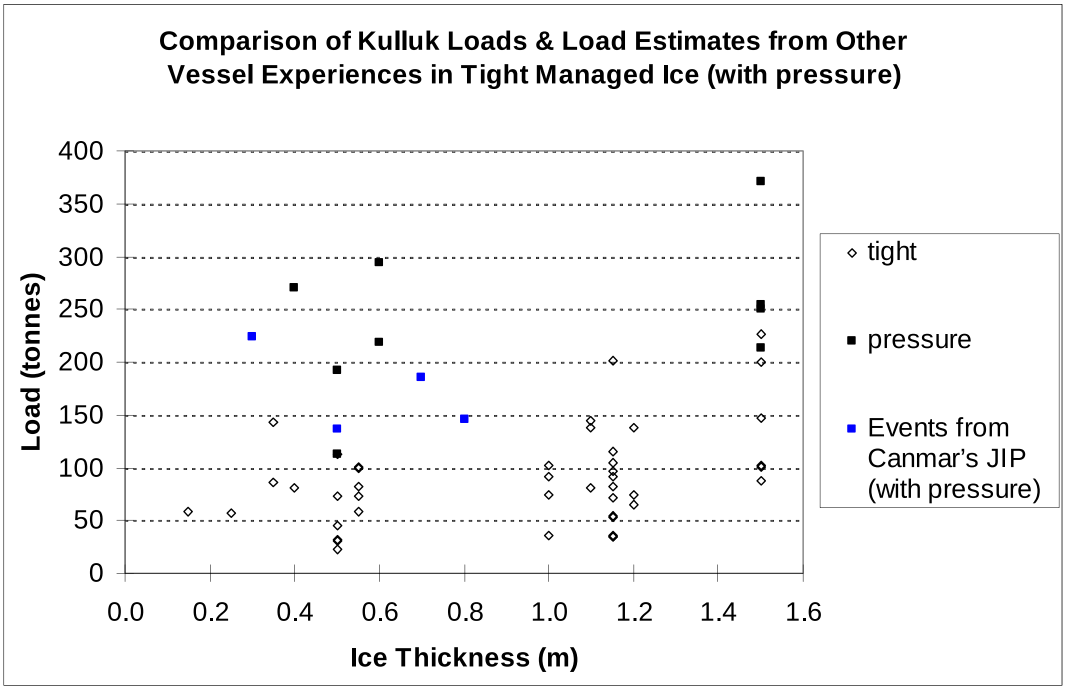


Figure 5.34

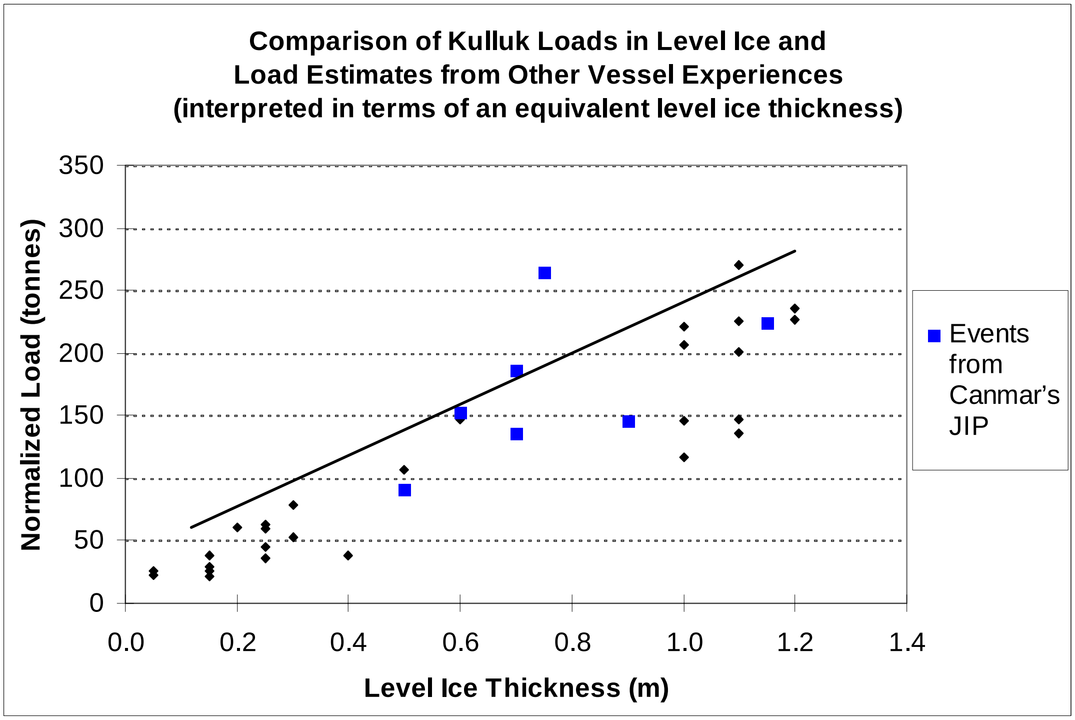


Figure 5.35

6.0 Comparison with Model Tests

6.1 General

The full scale data that was presented in the last section of this report is felt to be the best indicator of probable load levels on moored vessels in moving pack ice conditions. However, it is important to recognize that a large number of ice model testing programs have also been carried out to investigate the question of moored vessel stationkeeping in moving ice. Model tests began in the mid 1970s and at the time, were directed towards the feasibility of using different types of floating drilling systems in ice. An extensive series of model tests was then carried out with the Kulluk in the early 1980s, before its design was finalized. More recently, a variety of model tests have been undertaken to evaluate the feasibility of different floating development approaches in ice, including FPSO and tanker loading operations.

In another PERD study that has just been completed (Comfort et al, 1999), an extensive model test data set regarding loads on moored vessels in moving ice has been developed and assessed. Here, some of these model test results are compared to the full scale load data that has been developed in this work. Because of restrictions in the work scope, the comparisons given here are no more than cursory. However, they do provide a reasonable feel for the general level of correspondence between the model test and full scale load data.

6.2 Assessment Approach

In the study that dealt with model test data, various model test results were grouped together on the basis of the “type of vessel” being evaluated in model scale. The four main vessel (or scenario) categories that came out of the work were:

- tests with the Kulluk
- tests with semi-submersibles
- tests with turret moored drillships and FPSOs
- tests with moored tankers at loading terminals

Some of the model test results could be directly compared to the full scale data, for example, those pertaining to the Kulluk. For tests involving differently sized and shaped vessels (eg: drillships and FPSOs), the data had to be corrected to a common vessel form. In other cases, the vessels tested were too far removed from those in full scale for meaningful comparisons (eg: semis), or their particulars were not well enough known to allow “data standardization”. In summary, the model test results that could be reasonably compared with the full scale data included:

- tests on the Kulluk
- tests on moored drillships
- tests on the Terra Nova FPSO
- tests on open water and icebreaking tankers moored to a narrow SPM

Comparisons with other model testing results were “too much of a stretch” to be considered meaningful, for the reasons mentioned above.

The Comfort report, entitled “An Evaluation of Ice Model Test Data for Moored Structures”, contained very little information about the particulars of the vessels tested or the properties of the model ice used, such as its flexural strength. In the case of the Kulluk tests, the author’s familiarity with the original model testing data allowed ice strength corrections to be made where relevant. The author’s direct involvement in the “BHP’s moored tanker - SPM tests was also a benefit in terms of knowing the specifics of the vessels tested. However, for the drillship and FPSO model tests, reasonable assumptions about vessel hull forms had to be made to enable load data standardization.

The procedure that was used to “correct” the model test data for differently sized and shaped vessels to a common form is the same as that outlined in Section 5.3.1. Again, the Kulluk design was used as “the standard vessel”. In Appendix 3, where an example of this correction procedure is given, the load data conversion factors for all of the vessels that were tested in model scale are also summarized.

6.3 Load Intercomparisons

Here, the load data that was obtained in relevant model testing programs is briefly compared with the full scale Kulluk loading data. To make appropriate intercomparisons, the type of ice interactions that were either seen or modelled in various model tests have been associated with the equivalent full scale condition. For example, Kulluk test results in level unbroken ice have been directly compared with the full scale level ice loads, while the model test results in broken ice conditions (where basin wall effects caused tight ice and an updrift rubble wedge) have been compared with loads in the equivalent full scale “tight ice” situation. Similarly, when good ice clearance was observed in model tests involving broken ice (eg: the moored tanker tests where the presence of the SPM created some looseness in the ice, the FPSO tests in < 9/10ths), model test results were compared to the full scale loads with good clearance. The results of these comparisons are summarized as follow.

Kulluk Model Tests

- Figure 6.1 shows the loads that were measured in Kulluk model tests at the HSVA, IIHR and Arctec Canada basins in level unbroken ice, plotted against the full scale level ice load data. The “bars” around the model test points do not represent possible errors, but simply reflect the spread in the loads that were measured in different model test runs for the same basic ice condition. In general terms, the comparison is “not bad”, although the model test results do tend to overpredict the full scale load levels. More specifically:

  - the HSVA tests, which were used as the primary basis for the Kulluk’s “ice design”, show fairly good agreement
  - the IIHR tests are “slightly high”, but this may be the result of higher model ice flexural strengths than the 500 kPa value (to which the Kulluk and HSVA data was normalized)
  - the Arctec results are “quite high”, by a factor of at least two, but the wax ice that was used by Arctec at the time had a very high friction coefficient, which produced ice interactions that were not representative of what was seen in full scale

- Figure 6.2 shows the few full scale unbroken ridge loads that were measured on the Kulluk, plotted against an “expected band” of load levels, based on ridge model tests with the Kulluk at HSVA. This model test data was not contained in the Comfort report, but has been included here for completeness. It may be seen that the model test loads overpredict the full scale ridge load measurements. By way of background:

  - this may be related to the fact that the strength and thickness of consolidated layers in modelled ridges were always quite high, and difficult to control
  - it may also be related to the natural variabilities in the geometry and strength of ridges that occur in full scale

- Figure 6.3 shows the results of Kulluk model tests in tight broken ice conditions, plotted against full scale data for the same scenario. The trends that are indicated by the model test and full scale data are similar, but the model tests generally produce higher load levels. Again, the Arctec test results are “much too high” and “buck the trend”, because of the high friction properties of the wax ice used in these tests.

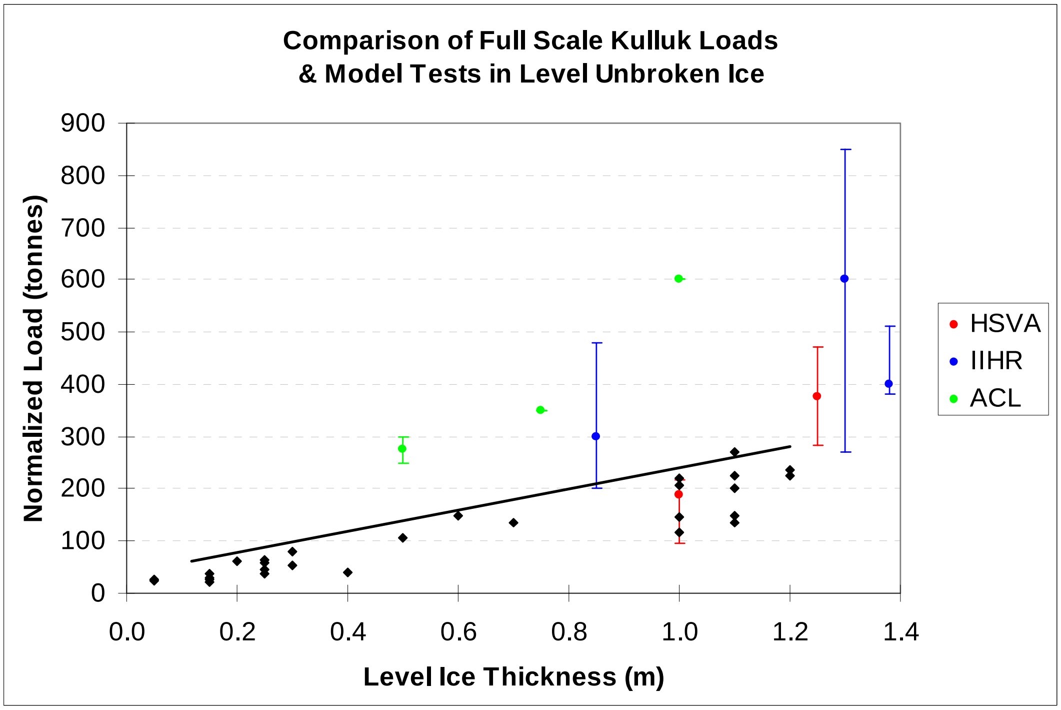


Figure 6.1

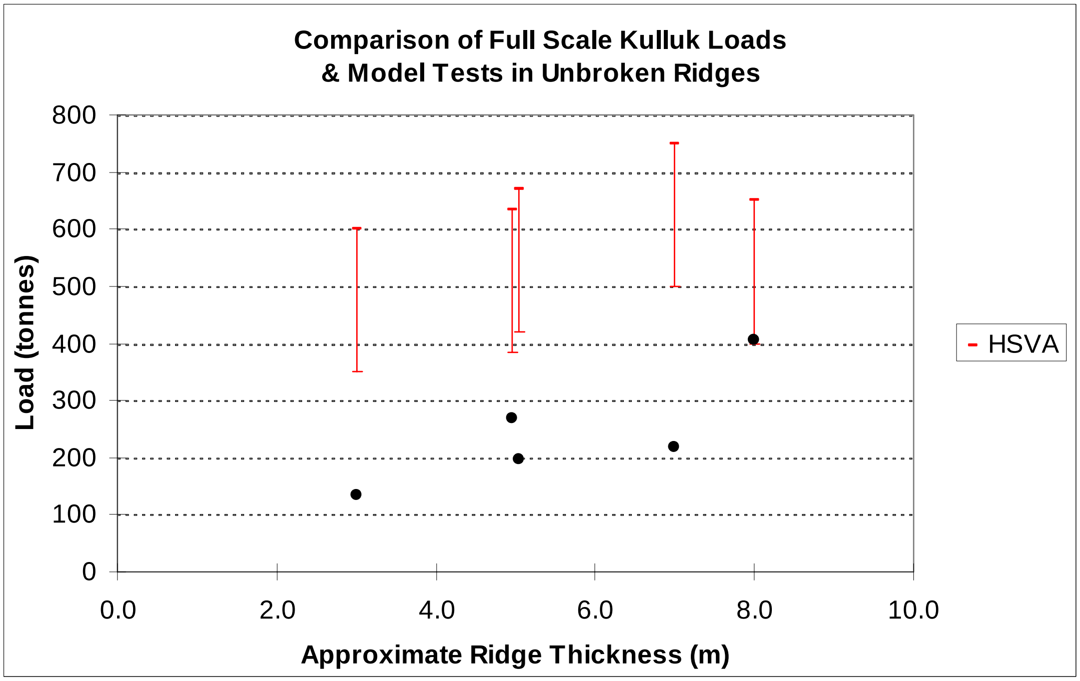


Figure 6.2 **To make these comparisons, it has been assumed that the full scale ridges have a simple triangular keel geometry and a consolidated layer thickness that is 1.5 times the surrounding level ice thickness.**

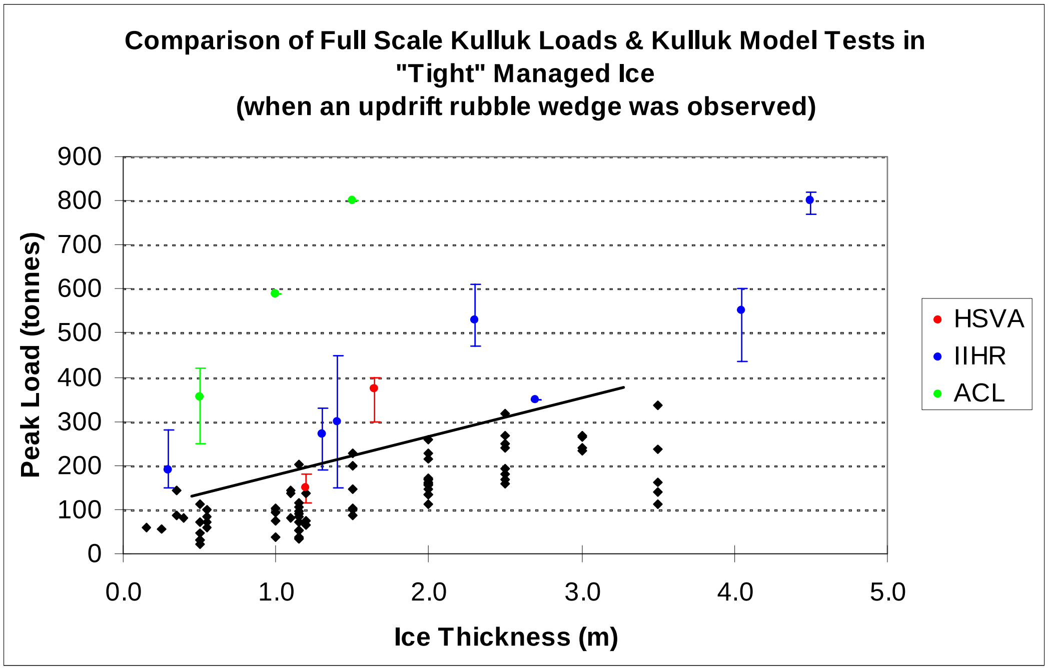


Figure 6.3

Model Tests with Moored Ship Shaped Vessels

- Figure 6.4 shows the results of model tests with ship shape vessels in tight broken ice conditions, corrected to the Kulluk's form, and compared with the loads measured in similar full scale situations. Although the number of model test data points is small and quite restricted in terms of their thickness range, the model and full scale load comparisons are not unreasonable.

- Figure 6.5 shows the loads from model tests on moored ship shape vessels where good ice clearance was seen, again corrected to the Kulluk's form, plotted against full scale Kulluk data for the same type of ice interaction situation. It may be seen that the overall trend and correspondence between the model test and full scale data is actually quite good, although the model test results do tend to be towards the high side of the full scale loads.

By way of summary, the level of agreement that can be seen between the majority of the model test and full scale load measurements is surprisingly good, for equivalent ice interaction situations. In most cases, the model test results tend to lie towards the upper end of the full scale load data. This however is not uncommon, based on comparisons between model test and full scale load information for other types of offshore structures. Moreover, model tests should be biased towards a certain level of conservatism, and should not result in unduly optimistic projections about the range of load levels that one might expect.

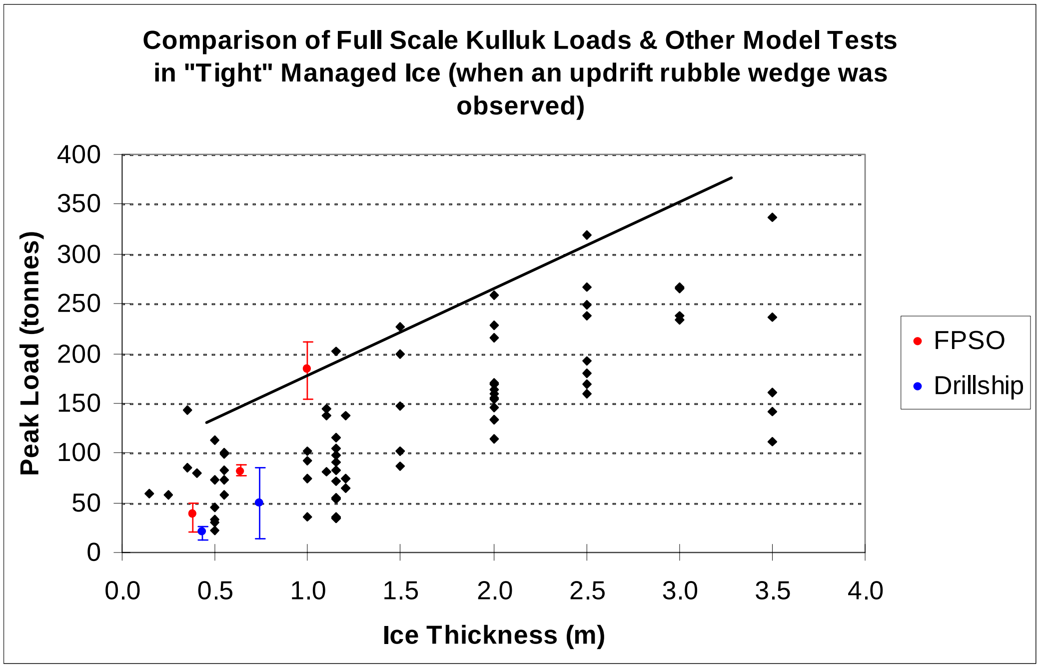


Figure 6.4

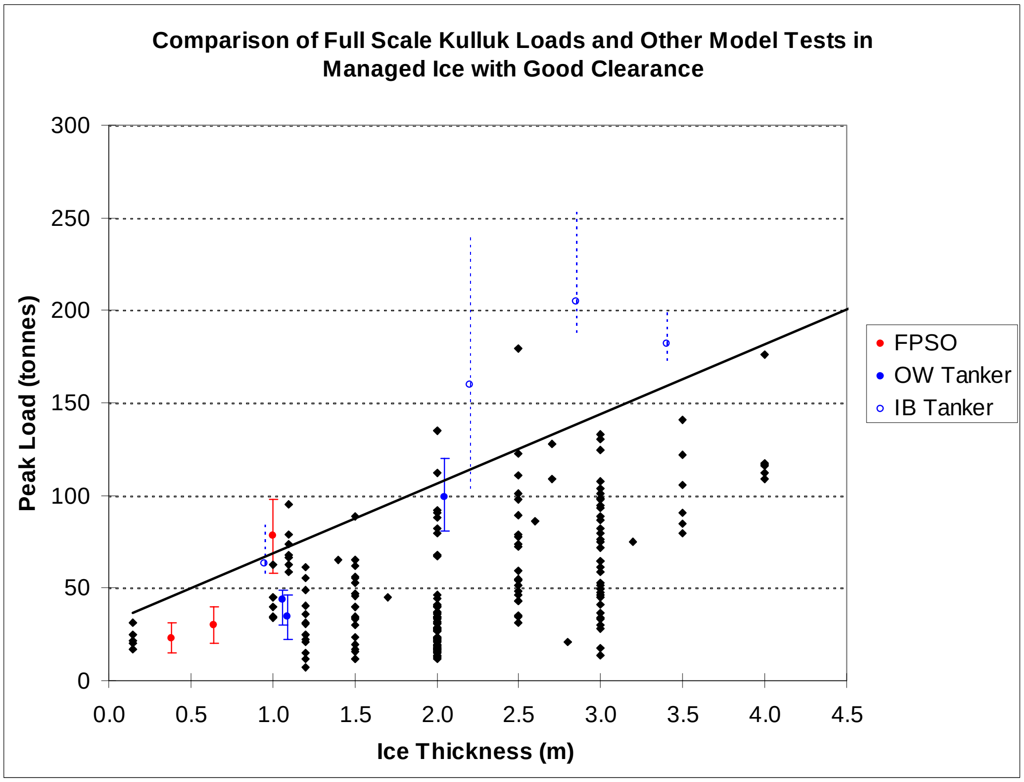


Figure 6.5

7.0 Implications for Grand Banks Development Systems

7.1 General

The full scale load data that was presented in Section 5 of this report can be used to obtain some perspective about expected load levels on moored vessels in Grand Banks pack ice. This topic area was quite thoroughly addressed in a recent PERD report entitled "Moored Vessel Stationkeeping in Grand Banks Pack Ice Conditions" (Wright et al, 1998). In terms of load levels, this work suggested that moored vessel operations in the type of pack ice conditions that are periodically encountered on the Grand Banks should be considerably less difficult than is currently perceived, provided systems with reasonable in-ice capabilities and adequate levels of ice management support are used. Expected 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 levels for typical mooring and loading arrangements, again providing tanker loading systems with reasonable in-ice capabilities and adequate ice management support are used.

Here, the question of load levels on moored vessels in Grand Banks pack ice conditions is revisited, in light of the full scale data set that has been developed in this study. In addition to lending more credibility to the load estimates that were given in the earlier PERD study, this information provides an example of how the full scale data set can be used to predict loads on moored vessels, in this case, for Grand Banks pack ice conditions. The material that is provided here is necessarily quite brief. For additional background information in topic areas such as pack ice conditions on the Grand Banks and representative moored vessel systems, the reader is referred to the previous PERD report.

7.2 Grand Banks Setting

The Grand Banks region is generally recognized as having one of the most hostile operating environments in the world. The primary environmental constraints in this area include high waves, icebergs and sea ice, all of which have influenced the exploration approaches used to date and the design philosophies for the development systems that have been planned. Strong winds, structural icing and poor visibility are also of concern, but are more important in terms of affecting operations than influencing design. In all cases, floating ice in the form of both icebergs and pack ice, has been viewed as the key environmental constraint 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 development systems that may be used on the Grand Banks will unquestionably be exposed to pack ice occurrences over typical project lifetimes. Pack ice intrusions are not seen annually but are typically experienced every several years, lasting anywhere from a week to a month or more. On the northern and eastern parts of the Grand Banks, 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 that are in the order of 5/10ths to 8/10ths are most common, while floes sizes in the range of 30m in extent are quite 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 can also be contained within the Grand Banks pack ice cover.

Statistics that have been developed for current and potential development locations on the Grand Banks (Wright et al, 1998) confirm that pack ice occurrences in the region 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 load assessment that is given later in this section, 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 1m 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

- ice drift speeds in the range of 1 m/sec and typically less, which are generally quite uniform in direction but can exhibit some curvature in their drift trajectory

7.3 Representative Systems

In order to estimate expected load levels on moored vessel systems in Grand Banks pack ice conditions, it is clear that representative vessels must be defined. This was done within the context of the following development scenarios.

- FPSO stationkeeping operations in moving pack ice
- tanker loading operations in pack ice at “exposed” sites (eg: the Hibernia OLS)

The types of moored vessels that have been considered as representative for the purposes of this work are the same as those highlighted in the earlier PERD report (Wright et al, 1998). Three “typical vessels” have been selected, with vessel size considered as the main variable. In terms of future Grand Banks developments, FPSO sizes will be largely determined by the characteristics of the particular oil field being developed, the peak daily production rates that are planned, and related oil storage and tanker export cycle requirements. For example, the Terra Nova oil field is relatively large and productive, with about 350 million barrels of recoverable oil reserves that will be produced at peak daily rates of 125,000 BOPD. To support these production rates and planned tanker export cycles of about six days, the Terra Nova FPSO will be quite large, with an onboard storage capacity of 960,000 barrels. Smaller fields like the Whiterose and Hebron prospects, with estimated recoverable reserves in the 150 million to 250 million barrel range, will require proportionately smaller FPSO vessel sizes and onboard storage capacities (Wright et al, 1997).

Table 7.1 highlights the representative FPSO vessels that have been selected for use. They range in size from 50,000 DWT to 160,000 DWT, with the Terra Nova FPSO representing the upper bound case. The two smaller FPSO vessels, with oil storage capacities of about 190,000 and 550,000 barrels, are intended to represent lower bound and median cases. These FPSO vessels, the Captain and Petrojarl 1, are more typical sizes for oil field developments in the 100 to 200 million barrel range, and are currently being used in the North Sea’s Captain and Blenheim development projects. 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 these types of vessels 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.

Table 7.1: Representative moored vessels.

	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)

7.4 Estimated Load Levels

As a final stage to this study, the full scale load data set that has been developed was used to estimate expected load levels on moored vessels in Grand Banks pack ice. This "data set application" was carried out within the context of the pack ice conditions and moored vessel systems outlined above.

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The analysis procedure, which is actually quite straightforward, is highlighted as follows.

- firstly, "correction factors" to transform the full scale Kulluk loading data (the primary data source) into "equivalent loads" on the three representative Grand Banks FPSOs were calculated. This calculation was based on the procedure outlined in Section 5.3.1, and the size and hull form of each one of the vessels (see Appendix 3).

- the type of ice interaction scenario and accordingly, full scale load data summary that is most appropriate to the "Grand Banks moored vessel consideration" was then selected from the full scale data set, namely:

  - the full scale loads that were measured in managed ice conditions with good ice clearance (Figure 5.5), which are comparable to most of the pack ice interaction situations that should be expected on the Grand Banks

  - the full scale loads that were measured in tight ice conditions with poor ice clearance (Figure 5.12), which in a conservative sense, are comparable to most of the extreme ice interaction situations expected on the Grand Banks

- the "upper bound load line" for the full scale load data was then used as a basis for estimating peak load levels on the three representative moored Grand Banks vessels, across the range of ice thicknesses expected in this area.

The results of this "data set application" are shown in Table 7.2, where expected peak load levels are given for three representative Grand Banks FPSOs across the expected range of ice conditions for the area. Although floe sizes on the Grand Banks are in the same range as well managed Beaufort Sea ice, good ice management support has been assumed. The presence of capable ice management vessels is both prudent and necessary, particularly to clear any updrift rubble accumulations that may be seen in "tight ice" and enhance ice clearance along the "exposed side" of a moored vessel in changing ice drift direction conditions.

Here, it is important to note that the full scale load data set does not include ice interaction situations where there were consequential curvatures in the ice drift trajectory. Model tests and some documentation from full scale ship trials (turning tests) suggests that loads on "long vessels" in changing drift direction situations may be amplified. Because of this, load estimates have been included in Table 7.2 to conservatively bound this type of "changing ice drift direction situation". Load amplification factors, relative to the constant ice drift direction case, have been determined for each representative FPSO. These factors are proportional to the ratio of vessel length to ice drift track radius, and are similar to those developed in Canmar's recent Arctic Tanker Loading JIP study on the basis of model tests. The typical and rapid drift direction situations that are shown in Table 7.2 are based a mean drift speed of 0.3 m/sec and assumed drift direction changes of 20°/hr and 45°/hr, respectively. It may be seen that the combination of very thick pack ice, poor ice clearance, and rapid changes in ice drift direction produces projected load levels that may tax the mooring capability of these FPSOs. However, ice management can be used to clear any rubble that may be loading the "longside" of an FPSO in this type of situation, and reduce load levels to much lower levels.

Table 7.2: ***Expected load levels on representative FPSO vessels, conservatively estimated from the full scale data set.***

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
Extreme (1.0m - 1.2m)			
- constant drift direction	250 - 280	300 - 330	350 - 390
- typical drift direction change	300 - 380	420 - 460	560 - 620
- 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
Extreme (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.

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 the FPSO vessel's mooring system

- 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

- 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 and in turn, substantially reduce load levels ("back down" to good ice clearance load levels)

It is recognized that the occurrence of growlers, bergy bits and small icebergs within the pack, and combined ice and wave conditions, will present additional challenges. However, floating development systems that are based on the use of ice strengthened vessels, capable mooring systems and good ice management support should allow moored vessel stationkeeping operations in most Grand Banks pack ice conditions, with little if any downtime. Downtime that may be caused by pack ice intrusions, which at some locations can have annual averages in the range of 20 to 30 days and annual extremes of 50 to 70 days, should not necessarily be assumed for FPSO and/or tanker loading operations. In terms of project economics, this suggests that NPV increases in the order of $50 to $150 million may be seen because of lower pack ice downtime levels, particularly for small oil field developments at the more exposed locations on the Grand Banks (Wright et al, 1997). In more direct terms, 20 to 30 days of production "uptime" for a floating development system that is producing oil at 80,000 BOPD would generate additional revenues of $32 to $48 million a year at $20/barrel. This level of revenue is a particularly important consideration over the first few years of any development project. In addition, should a bad pack ice year be encountered within the first year or two of a small development project, with ice related downtime levels of 60 days or so, the large revenue losses that could accrue would have a very adverse effect on project economics.

8.0 Summary

This report has presented the results of a PERD sponsored study that addresses the question of loads on moored vessels in moving pack ice, on the basis of existing full scale data and with particular reference to floating development systems on the Grand Banks. In terms of scope, the study has included:

- a review of the full scale data that is available regarding loads on moored vessels in pack ice, including:

  - information that was obtained during operations from the Kulluk and Canmar drillships in Beaufort Sea ice conditions
  - relevant information that was obtained from various vessel performance trials and other ship operating experiences in ice

- the development of a full scale data set from selected "events" that gives quantitative information about loads on moored vessels in different pack ice conditions

- an evaluation that summarizes the full scale load information in the form of combined scatter plots, and ties all of the data together in the context of expected load levels on moored vessels in pack ice

- a comparison of the full scale load data with relevant information from a companion PERD project, which deals with moored vessel model tests

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

The key results are briefly highlighted as follows.

Full Scale Data Set

A unique data set has been developed that contains an unparalleled source of "real world" information about full scale loads on moored vessels in a wide range of moving pack ice conditions. This data set is important not only for future development activities on the Grand Banks, but also for any other ice infested regions of the world where moored vessel stationkeeping operations are being considered. By way of summary:

- information that was acquired in conjunction with drilling operations from the Kulluk comprised the majority of the data set, and includes 384 different loading events. This data forms the "backbone" of the work, because of both its quality and quantity.

- relevant information from vessel performance trials and other in-ice ship operations is not particularly plentiful, with only 26 "ship events" being contained in the full scale data set. However, these ship entries are a meaningful component of the data set, since comparisons with the Kulluk loading information shows that all of the data ties together sensibly, and forms a consistent and credible pattern.

- although Canmar gained a great deal of experience with their Beaufort Sea drillships, there was very little documentation around their operations, particularly with regard to the load levels experienced by these moored vessels in ice. Since there is basically no quantitative information from Canmar's drillships that is either available or can be meaningfully used in this study, this data source has necessarily been excluded.

Evaluation of Full Scale Data

The full scale data set has been "exercised" in this study, to evaluate the loading levels and trends that it suggests as a function of different ice parameters. Scatter plots of the Kulluk data have been given for the following ice and ice interaction situations.

- loads in level unbroken ice
- loads in unbroken ridges
- loads in managed ice with good clearance
- loads from floe impacts
- loads in "tight" managed ice and in "ice pressure'

Information about the nature of these types of loading events on the Kulluk has also been provided, including "rise times" to peak loads, peak to mean load ratios, and event durations.

This evaluation of the full scale Kulluk load data has shown very clear and logical trends. As noted above, comparisons between the Kulluk and ship data have also been made, which indicate that all of the full scale load information ties together well, and forms a consistent and credible pattern. Although the data set contains a considerable amount of information about ice management support levels and techniques, the ice management consideration has not been addressed in much detail in this work.

Comparison with Model Tests

The full scale load data has also been compared with the results of relevant physical model tests that have been carried out with moored vessels in moving ice conditions. Comparisons have been made for level ice, ridge and managed 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 between the majority of the model test and full scale load measurements has been shown to be surprisingly good, for equivalent ice interaction situations. In most cases, the model test results tend to lie towards the upper end of the full scale load data. This however is not uncommon, based on comparisons between model test and full scale load information for other types of offshore structures.

Implications for Grand Banks Developments

The full scale data set has also been used to obtain some perspective about expected load levels on moored vessels in Grand Banks pack ice conditions. This "data set application" serves two purposes. Firstly, it provides an example of how the full scale data can be used and secondly, it presents relevant loading information for typical Grand Banks systems. For the purposes of this work, several representative vessels were 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 to a thousand tonnes for realistic scenarios, depending upon ice thickness, ice movement and ice clearance conditions. Since these load levels are within the capability of most mooring systems, the work suggests that moored vessel operations in the type of pack ice conditions that are 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 are used. However, it has also been recognized that the occurrence of growlers, bergy bits and icebergs within the pack, as well as combined ice and wave conditions, will present new challenges.

9.0 References

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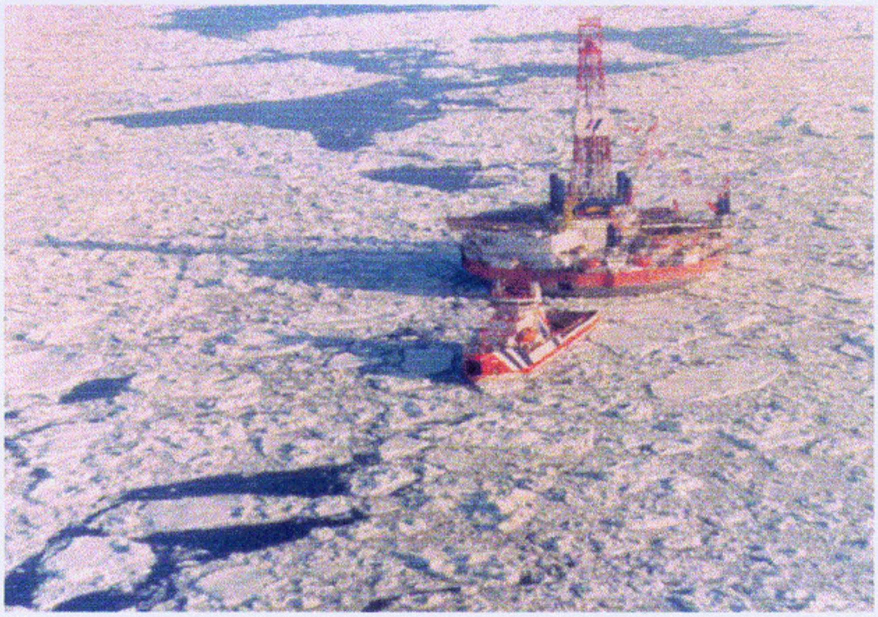
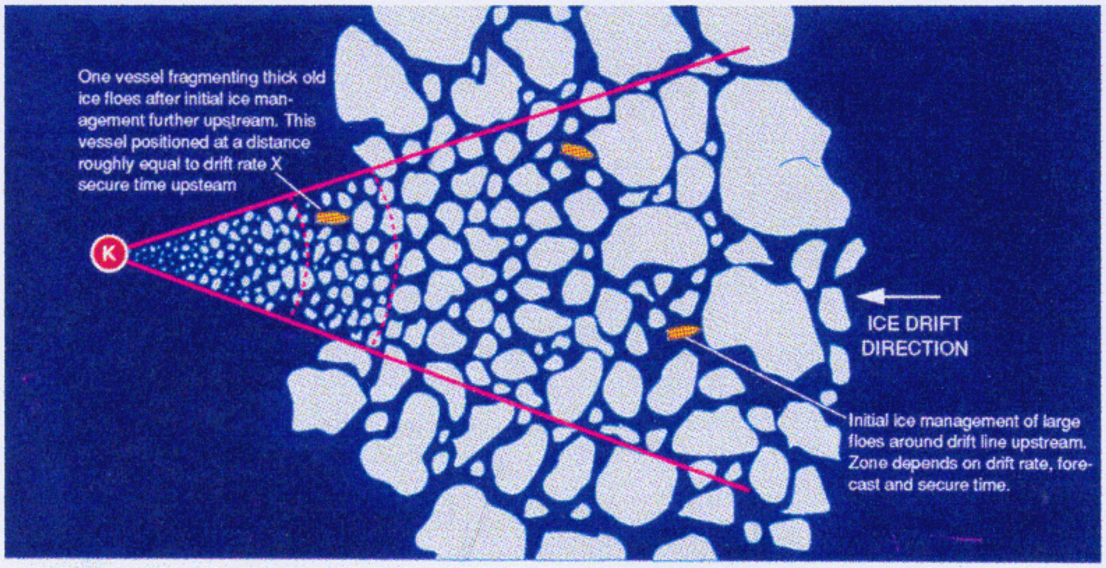
Appendix 1

(examples of the ice management techniques cited in the data set)

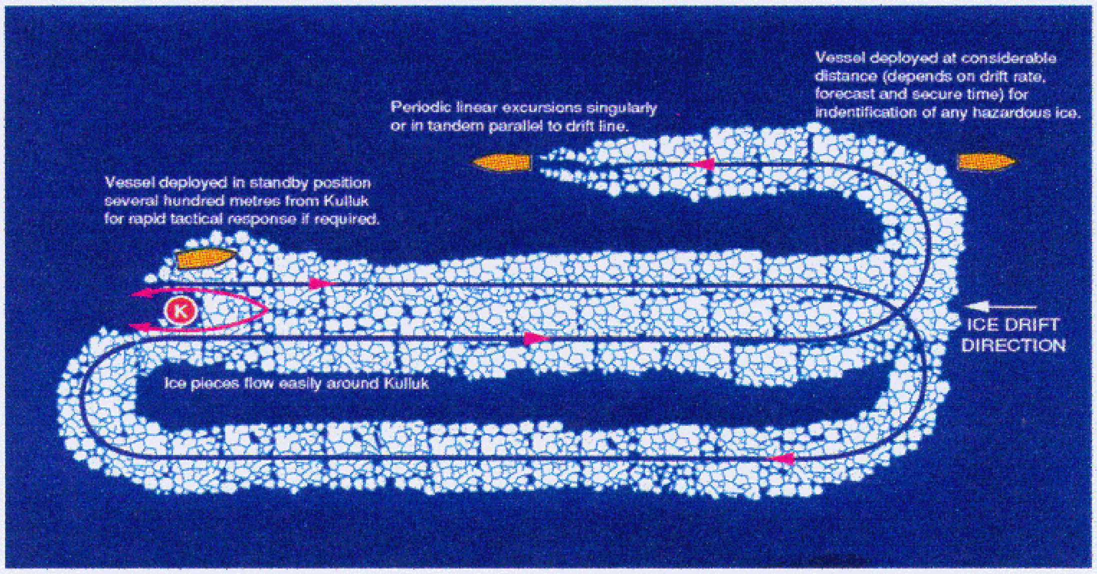




One vessel fragmenting thick old ice floes after initial ice management further upstream. This vessel positioned at a distance roughly equal to drift rate X secure time upsteam

Initial ice management of large floes around drift line upstream. Zone depends on drift rate, forecast and secure time.

"Picket boat" ice management



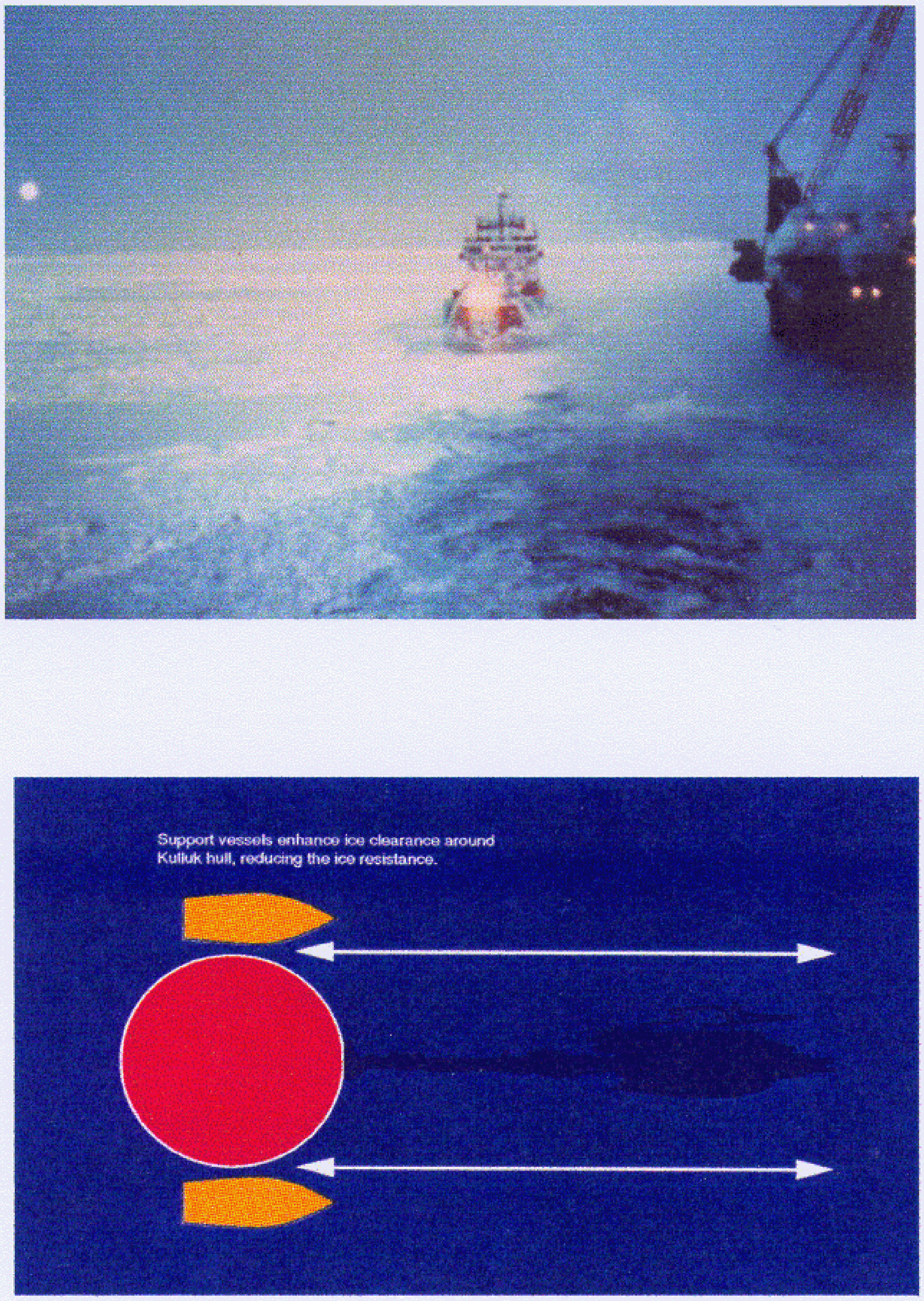
Vessel deployed at considerable distance (depends on drift rate, forecast and secure time) for indentification of any hazardous ice.

Periodic linear excursions singularly or in tandem parallel to drift line.

Vessel deployed in standby position several hundred metres from Kulluk for rapid tactical response if required.

Ice pieces flow easily around Kulluk

Tandem (or singular) linear tracks in ice



Close passes to promote / enhance ice clearance

Appendix 2

**(notes on the ship operating events
selected from Canmar's JIP study)**

Event Notes

#23.2 Arctic Breaker in McKinley Channel, Nov.1981.

Arctic Breaker pushed by Supplier 4 (100% power, about 50 tonnes push), and towed by Supplier 2, through an entrance channel. Tow speed not recorded. Tow line breaks (approx. 228 tonnes breaking load). Therefore peak towing load is 278 tonnes or above. Ice was reported as FY 0.6 m thick, with rafting and ridging up to 1.2 m and extent 50%. Ice was under some pressure. Ice strength estimate 500 kPa. Temp. -10^{o}C. Equivalent level ice thickness estimate given as 0.7m.

Vessel has dimensions of 400'*90'*15', buttock angles of 25 degrees, and a flare of 30 degrees. No special hull coating. Correcting peak towing load of 278 tonnes or above to Kulluk conditions gives a load of 186 tonnes or above.

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#29 Kigoriak maintaining position in drifting ice, close to Kulluk.

Kigoriak was close to and updrift of Kulluk, maintaining position under rig crane, and in managed ice (Kalvik and Miscaroo updrift) composed of 3/10, 2Y, 2m; 5/10, FY, 0.4m; 1/10, GW, 0.2m. 0.6 knots drift speed. Equivalent level ice thickness estimate of 0.6m. Ice would build up between Kulluk and Kigoriak, resulting in pressure situation with equivalent level ice thickness estimate of 0.9m. Kigoriak required main propulsion thrusts (in bursts) of about 50 tonnes in unpressured ice and 80 tonnes thrust in pressured ice in order to correct for ice drift and stay on location. Correcting from Kigoriak to Kulluk dimensions and shape, these loads become 91 tonnes in 0.6m unpressured ice, and 146 tonnes in 0.6m pressured ice (equivalent to 0.9m of unpressured level ice).

#30 Ikaluk (with small barge alongside) moored at stern and by bow anchor, stern-to Kulluk in ice which is drifting and changing direction by 90 degrees in 6 hours.

The stern mooring line breaks when the ice drift is from the stern quarter and Kulluk is not directly shielding. At this time, the mooring line which breaks is about 20-30 degrees from the ice drift direction. The small barge is shielded from drift by Ikaluk, so its influence upon events is probably negligible. Ice loads are magnified by rubble build up (or pressure increase) in front of and between the Ikaluk and Kulluk).

The net load on the Ikaluk when the mooring line broke is estimated at 125 tonnes in the longitudinal direction (line failure load plus influence of propulsion and thrusters). The additional influence of the gradual drift direction change would add to this, but probably little due to the relatively slow rate of change of direction. Ice conditions were 9/10, 0.3m well updrift, but ice management by the Miscaroo and Canmar Supplier actually increased this thickness greatly. Concentration became 10/10 and rafting further increased against Ikaluk and Kulluk. Drift speed 0.5 knots. Equivalent level ice thickness for rafted ice under pressure was estimated at 1.15m. The failure load of 125 tonnes, corrected to the dimensions and shape of Kulluk, becomes 224 tonnes.

#31 Explorer 4 driven off location in November, 1979.

Explorer 4's mooring lines had underwater fairleads. Ice management provided by Kigoriak (@ 65%) + Suppliers 1,2,3,4 &7. Ice broken previous day returns as heavy re-frozen rubble, double original ice thickness (about 1m) + ridges. Estimated equivalent level ice thickness, drifting at 0.35 knots on the bow, is 0.6m, and mooring load estimate is about 450 tonnes (well beyond its capacity ?). Pressure condition arises and all vessels brought to stop. Ice drift on bow, exceeds holding power, line released and Explorer moves off location. Mooring load of 450 tonnes, corrected to dimensions and shape of Kulluk, is 153 tonnes.

#33.1 Kulluk unpowered conical rig towed by Kalvik, with Miscaroo breaking ahead 3 miles and returning to widen track.

10/10 ice, 6/10 FY 50cms, 3/10 SY, 1/10 MY, some pressure, -12^{o}C. Wind on beam, no ice drift. Equivalent level ice thickness estimated in range 0.5-0.9m. Limiting condition, little progress made, Kalvik bollard pull in open water is 186 tonnes, less 50 tonnes ice resistance and speed thrust loss = 136 tonnes.

#34.4 Robert Lemeur moored to SSDC in drifting ice 30 degrees off of stern.

Mooring line breaks, longitudinal load of 100 tonnes. 9/10 FY and MY floes moving at 0.3 kts. Kigoriak and Supplier 4 breaking ice. Equivalent level ice thickness estimated at 0.75m. Load of 100 tonnes, corrected to dimensions and shape of Kulluk, is 265 tonnes.

Appendix 3

(an example of the ship data standardization procedure and related load correction factors)

An Example of Load Data "Standardization"

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 "standardize" the full scale ship data to the Kulluk's size and hull form, and vice versa, are given as follows.

Ship resistance in ice is proportional to:

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

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 correct for the influence of vessel size and shape is given as follows, for the Terra Nova FPSO. Since the Kulluk loading data 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 that have been 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 “standardization” or “correction” factor that can then be used to convert loads from one vessel to the other is given as:

Loads on the Kulluk to loads on the FPSO = 414.7 / 81.8 = 5.07
Loads on the FPSO to loads on the Kulluk = 81.8 / 414.7 = 0.197

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

Some of the “standardization factors” that have been used to correct the full scale and model test data that is presented in this report are given as follows.

Loads on Kulluk → Loads on Vessel

Model Tests

Terra Nova FPSO	5.1
Drillship (ice action Á to its axis)	2.9
Icebreaking moored tankers	1.7
Open water moored tankers	4.3

Full Scale Vessels

Kigoriak	0.55
Ikaluk	0.56
Explorer 4	0.34
Arctic Breaker	0.56

Other Vessels

Petrojarl 1 FPSO	3.7
Captain FPSO	4.3

The “standardization factors” for the loading data from all of the other vessels that have been considered in this report are given in the data set, along with the vessel particulars that are required to compute them.