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# **MOLIKPAQ ICE LOADING EXPERIENCE**

**JULY 1996**

**Submitted To**

**NATIONAL ENERGY BOARD  
3RD FLOOR 311 - 6TH AVENUE SW  
CALGARY, ALBERTA  
T2P 3H2**

**PERD/CHC Report 14-62**

**Scientific Authority: Dr. Ibrahim Konuk**

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B.D. Wright**

## EXECUTIVE SUMMARY

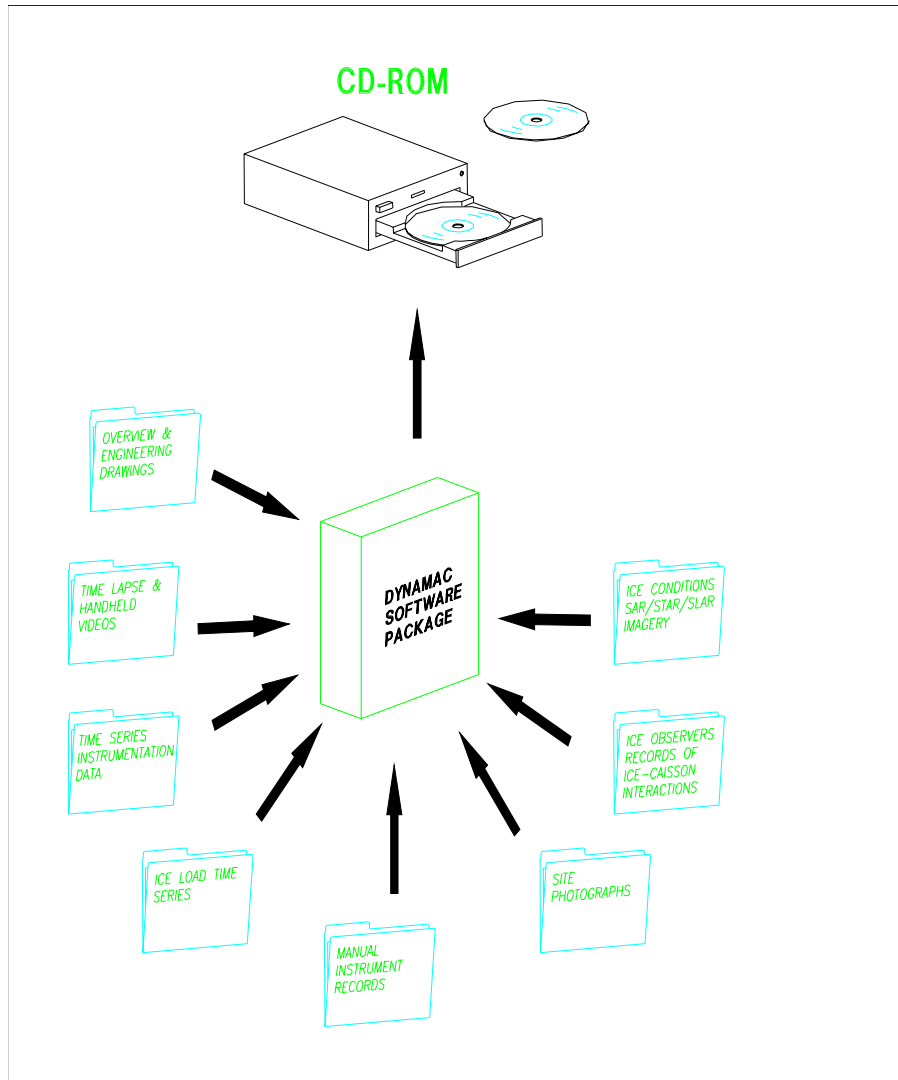
This report to the National Energy Board presents a compendium of ice loading events experienced by the Gulf Canada Resources Ltd. offshore platform "Molikpaq". To date, the primary interest in the Molikpaq has focused on a single event (the 0800 hr ice loading event on April 12th, 1986 at Amauligak I-65) which has perhaps led to some unbalanced views about the response of the Molikpaq during its four deployments in the Canadian Beaufort Sea. The intent of this report is to make the ice mechanics community more aware of the range of ice-structure interactions and ice load levels that the Molikpaq has experienced during the four winter deployments.

Four winters of operation at four different locations have produced an enormous amount of data, far more than can be realistically used within a research context. However, much of the ice interaction data are similar. An objective of the work carried out for this report was to review the available information and filter out about 30 days with events which capture the key aspects of Molikpaq ice-structure interaction and for which the available information is suitable for further research use. Ice-structure interaction events where ice failed directly against the caisson are of most interest and are available from the first two deployments at Tarsiut P-45 in 1984/85 and at Amauligak I-65 in 1985/86. At these locations the Molikpaq was deployed at a setdown draft of 19.5 metres, which resulted in no permanent accumulation of rubble ice around the caisson. A total of 10 operating days at Tarsiut P-45 and 19 operating days at Amauligak I-65 have been selected that contain representative periods with both ice documentation and Molikpaq instrumentation response data.

A further objective of this study is to summarize how the reported loads were derived from the sensor data, and to address concerns about potential structural resonance and overall load estimate accuracy. The Molikpaq was deployed for hydrocarbon exploration and the acquisition of the ice structure interaction data was peripheral to its principal activity which was oil drilling. One consequence of this is that the extent of the sensor arrays and the completeness of the ice documentation was pragmatic, and perhaps less complete than ice researchers might wish. This in turn has led to some uncertainty over the magnitude of reported ice loads on the Molikpaq, which has been exacerbated by the divergent views on ice loads within the ice community. Therefore, this report presents an overview of how ice loads have been calculated and importantly identifies the traceability of these reported loads to reference calibrations.

To provide researchers with confidence in their understanding of the data, a computer program running under the Microsoft Windows environment was developed to read and process the information obtained from the Molikpaq data acquisition system. The program, called DynaMAC, operates on the Molikpaq data sets which have been transferred from the original HP format to the industry-standard MS-DOS form and duplicates much of the functionality of the software developed by Gulf Canada Resources Ltd. Default calibration factors in DynaMAC correspond to values used for the Gulf Canada Resources Ltd. sponsored Dynamics Project and as such, this software provides a starting point for researchers to verify data records by reproducing the ice load plots previously reported. The program DynaMAC was further developed to provide a means of accessing a database that contains the ice documentation, and site photography from the Amauligak I-65 ice events. This information, together with data on sensor status and location, availability of video records, and the response data has been stored on a CD-ROM, as illustrated below.

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The underlying interest in the Molikpaq data is to establish a realistic range of ice load levels and how various ice failure modes affect the ice load on arctic offshore platforms. Although further analysis is required, a preliminary indication of the effect of failure mode on ice pressure is presented here based primarily on the review of the ice interaction events observed during the Molikpaq deployments at the Tarsiut P-45 and Amauligak I-65 locations.

The project team acknowledges the considerable support provided by Dr. Ibrahim Konuk of the National Energy Board, and Dr. Gary Timco of the National Research Council of Canada during the archiving of the Molikpaq Ice Loading Experience dataset. Partial sponsorship for this project was provided by the Government of Canada through the Program on Energy, Research and Development.

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## **1. INTRODUCTION**

### **1.1 Background**

During the 1970s and 1980s, Gulf Canada Resources Ltd., Esso Resources Canada Ltd. and Dome Petroleum explored for hydrocarbon reserves across the Canadian Beaufort Shelf. All three companies used artificial island and caisson technology for some of their exploration, to provide ice-resistant platforms suitable for extended winter season drilling.

Using artificial islands as drill platforms was pioneered in the Canadian arctic by Esso Canada Resources Ltd. in the near-shore shallow waters off the MacKenzie Delta. Early islands were constructed of dumped sand or gravel contained within sandbag bunds. The movement of the landfast ice produced ice rubble fields around the islands, limiting the measurement of ice loads. As exploration progressed offshore, islands were constructed in deeper water. Island costs increased rapidly with these increased water depths and this led to the adoption of caisson designs.

Early caissons such as the Esso Caisson Retained Island (CRI) and the Tarsiut N-44 concrete caissons were founded at shallow depth on large submerged berms. The combination of structure mass, width and height of the berms and the shallow water limited the ability of ice to clear causing large grounded rubble fields. These rubble fields generally formed during the freeze-up period, providing protection from direct interaction of the structure with winter ice.

The Molikpaq concept was different from this prior island and caisson experience. The Molikpaq was developed by Gulf Canada Resources Ltd. as a deep draft caisson to operate in the water depth range of 20 m to 40 m. A consequence of adopting this deep caisson design was that a protective rubble formation was not expected to form. Consequently, the caisson interacts directly with moving winter pack ice.

Design and fabrication of the Molikpaq extended over a period of some 3½ years. Conceptual design of the structure began in late 1980, with detailed design and bidding in early 1981. Fabrication began

in late 1981 in the AICHI yard of Isikawajima-Harima Heavy Industries in Nagoya, Japan and was completed in the spring of 1984.

The Molikpaq is essentially a continuous steel annulus, octagonal in plan, supporting a deck which carries the entire drilling and "topsides" facilities. It has a height from base to deck level of 29 m, while plan dimensions range from 111 m at the base to 86.6 m at deck level. An ice and wave deflector is mounted around the perimeter of the deck. The structure is illustrated in Figure 1.1.

The deck carries all topside equipment and also provides storage areas for tubular, mud and bulk consumables. Fuel oil is stored in the upper sections of the caisson in 12 separate tanks protected by a double hull arrangement. The outer face of the caisson is designed to accommodate extreme ice features and intense local loading. A system of closely-spaced ribs support the exterior skin plate and serve to distribute ice loads through an arrangement of frames to intermediate and main vertical bulkheads spaced at 1.22 m and 2.44 m, respectively.

The caisson is divided into a series of twelve major ballast compartments. Setdown and refloating of the caisson are achieved entirely by the movement of water ballast to and from these compartments. The shape of the caisson is such that a large ballast volume is provided at the base which, when empty, results in a minimum draft of about 7 m in the floating "lightship" condition. Ballast pumps are located in two main pump rooms and, through a ring main and isolating valve system, can undertake all ballasting, deballasting, transfer, and trimming operations. The pumps and major valves are remotely-controlled from a central control room. For ease of maintenance, the valves are located in two separate dry valve rooms.

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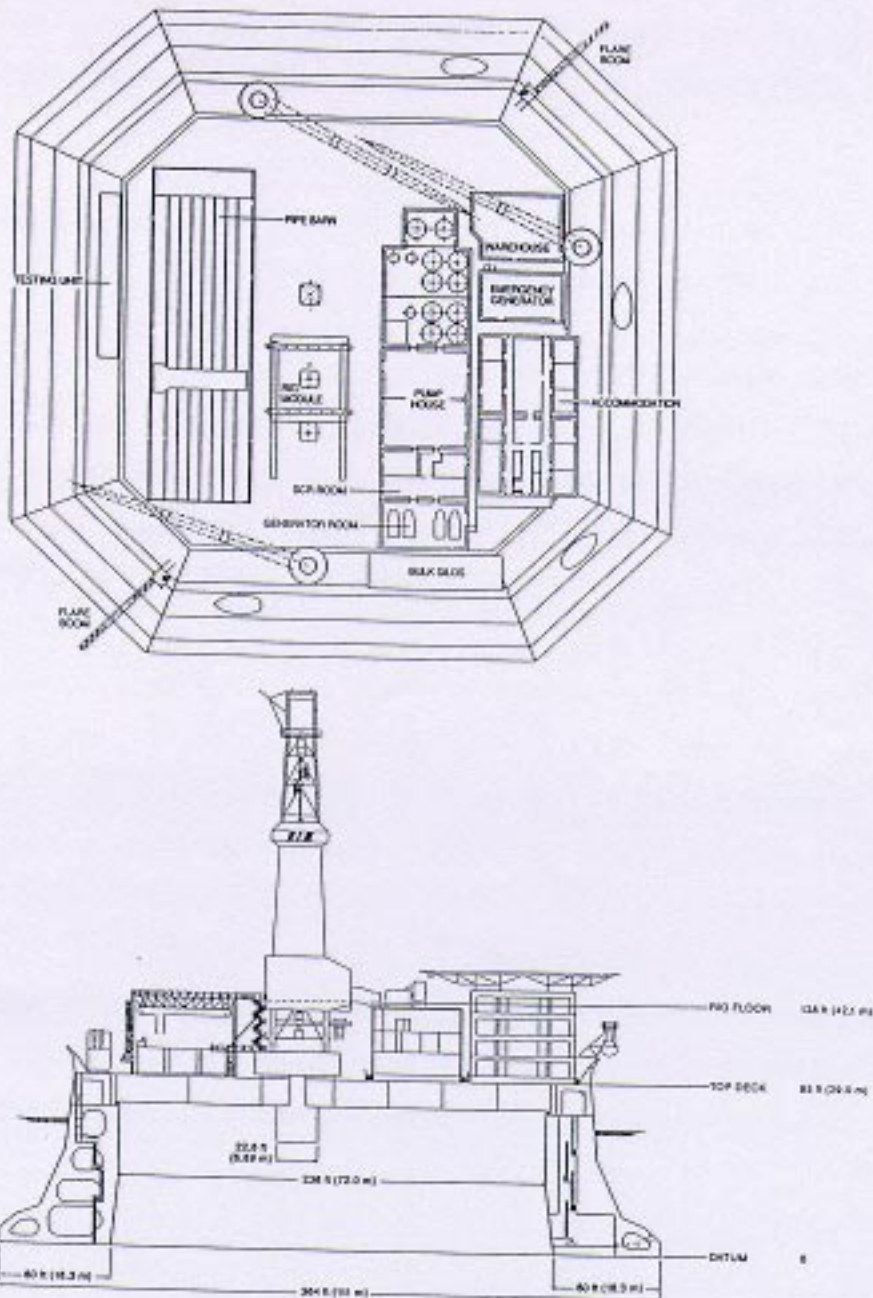


Figure 1.1: Plan view and cross section of the Molikpaq caisson.

The Molikpaq can be setdown directly on the seabed, or on a prepared berm pre-built at the site to suite local bathymetry, and subsurface soil conditions. The core space is then infilled with sand fill material.

The geotechnical stability of the Molikpaq is achieved from the following two sources:

- . The friction (soil/steel) generated by the weight of the steel caisson on the supporting berm; and
- . the mass of the sandfill placed within the core of the caisson, in particular the frictional resistance generated by its weight on the supporting berm

Assuming moderately dense sand in the core and underlying berm, the caisson/berm combination was originally designed (Golder, 1981) to achieve an ultimate horizontal sliding resistance to ice loading of 890 MN.

The Molikpaq entered the Canadian Beaufort Sea in August 1984 and has drilled nine wells at four deployment sites, located as shown in Figure 1.2. Over the course of these four winter deployments, the Molikpaq has been exposed to a wide variety of ice conditions, including both first and multi-year ice. Three of the Molikpaq's four deployments have been in the Beaufort's intermediate water depths, where the structure was located in the transition zone's moving pack ice cover. The fourth Molikpaq deployment location was well within the "stationary" landfast ice zone, in relatively shallow water (approx. 12 m). This final location did not require the construction of a berm to support the Molikpaq. Key construction parameters are shown in summary in Table 1.1.

At the Molikpaq's first two well sites at Tarsiut P-45 (Figure 1.3) in 1985/85 and at Amauligak I-65 in 1985/86 (Figure 1.4), the caisson was deployed on a sand berm at a set down draft of 19.5 m from mean sea level. As anticipated during design, there was no permanent accumulation of grounded ice rubble around the Molikpaq and the structure was directly exposed to moving pack ice throughout the 1984/85 and 1985/86 winter periods. However, at the third and fourth locations, Amauligak F-24 in 1987/88

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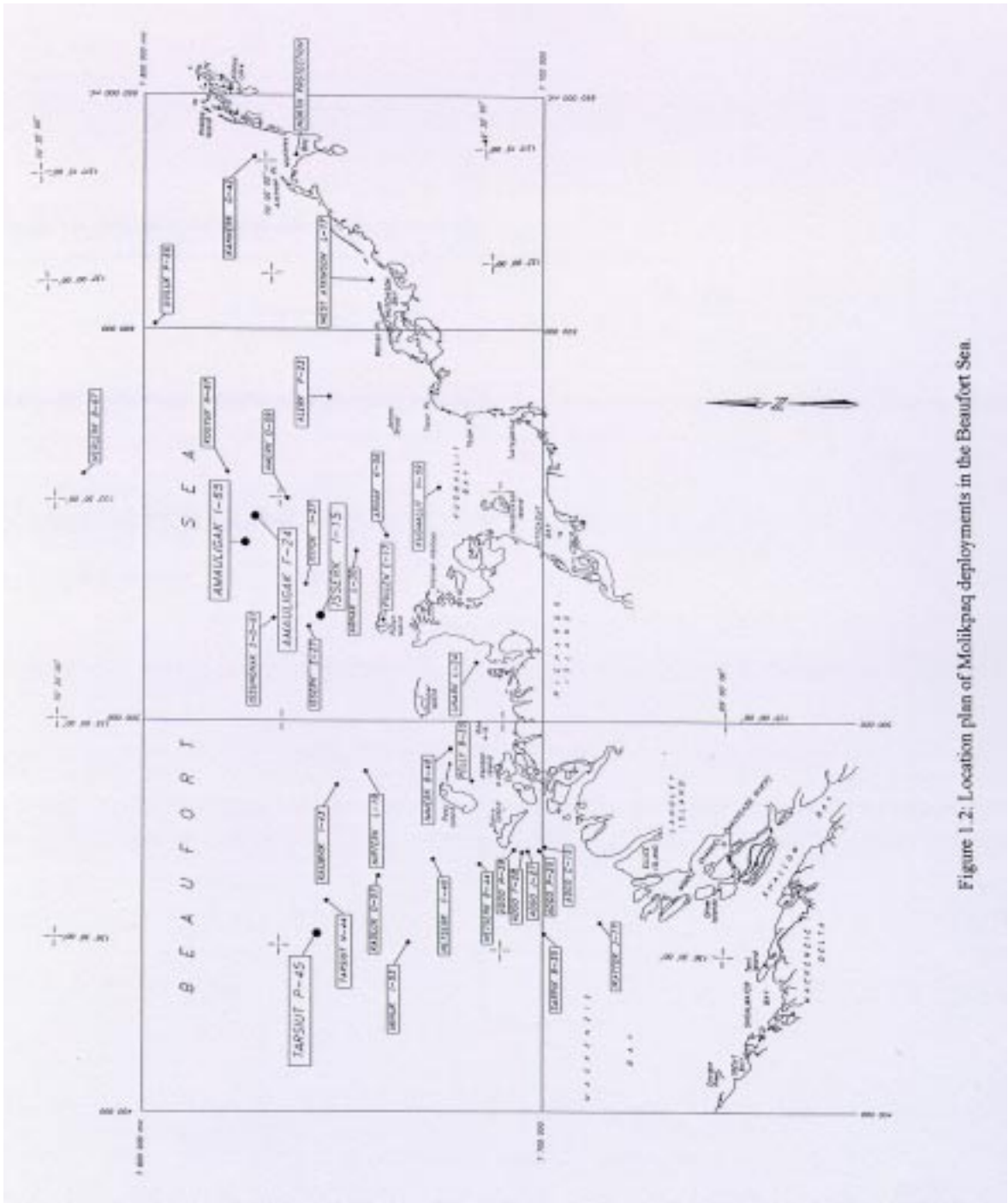


Figure 1.2: Location plan of Molikpaq deployments in the Beaufort Sea.

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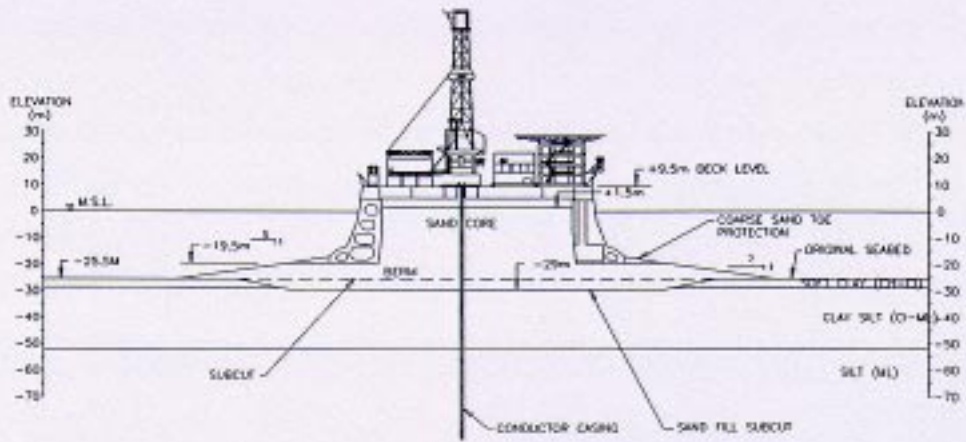


Figure 1.3: Molikpaq at Tarsiut P-45 1984-1985.

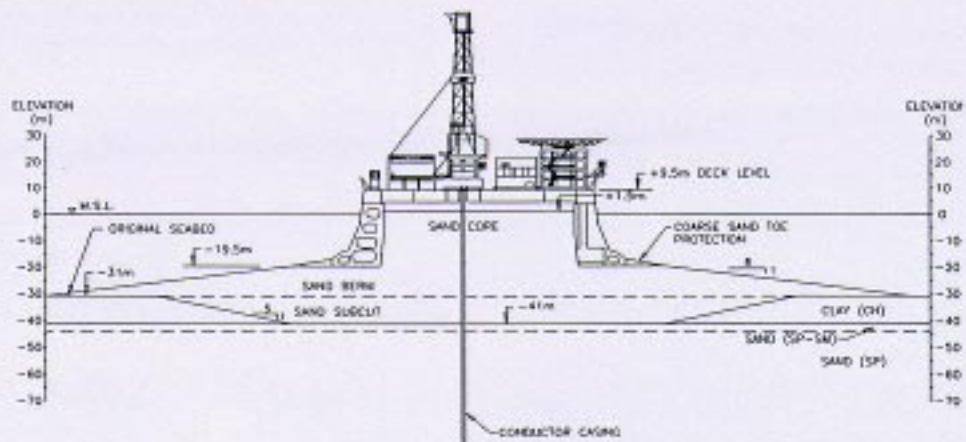


Figure 1.4: Molikpaq at Amaulik I-65 1985-1986.

(Figure 1.5) and Isserk I-15 in 1989/90 (Figure 1.6), the Molikpaq was deployed at shallower set down drafts which impeded ice clearance and resulted in the formation of grounded rubble around the structure. These rubble formations remained stable over the course of the winter precluding further direct ice interactions with the caisson. At these last two locations, the ice cover around the Molikpaq was also largely stationary during the two winter seasons, limiting the exposure of both the structure and the surrounding rubble field to moving ice.

**Table 1.1 - Summary of Molikpaq Deployments**

Site	Year Deployed	Water Depth (m)	Setdown Depth (m)	Subcut Depth Below Seabed (m)	Berm Height Above Seabed (m)	Core Height Above MSL (m)	Fill Quantity (m <sup>3</sup> )
Tarsiut P-45	1984	25.5	19.5	3.5	6.0	2.0	450,000
Amauligak I-65	1985	31.0	19.5	9.0	11.5	1.5	1,400,000
Amauligak F-24	1987	32.0	15.8	16.0	16.2	4.8	2,200,000
Isserk I-15	1989	11.7	13.4	1.7	N/A	-3.8	70,000

During all of its deployments, the Molikpaq has been well instrumented which, together with documentation of the interacting ice cover, has provided considerable insight into full scale ice-structure interaction processes and loads. The measurement and ice documentation systems improved throughout the four deployments, with additional gauges and software being introduced as operating experience was gained.

The net effect of the different ice conditions experienced for the various deployment configurations is that the Molikpaq ice-structure interaction database provides information as follows:

- **Tarsiut P-45** has event data on direct first year ice interactions with the near vertically sided caisson walls. Various failure models such as crushing, mixed modal, flexural and creep events recorded at Tarsiut P-45 are an important part of the available records.

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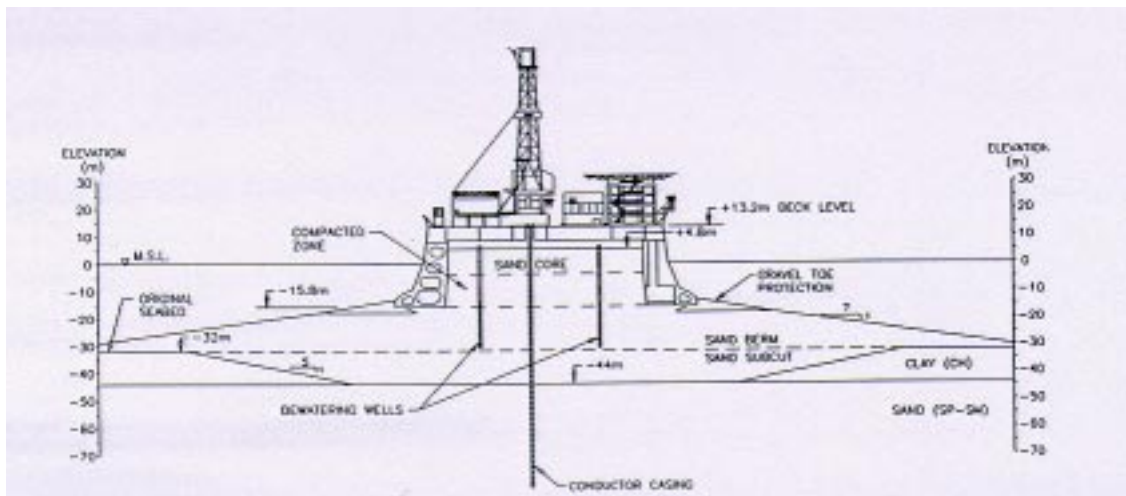


Figure 1.5: Molikpaq at Amaulikak F-24 1987-1988.

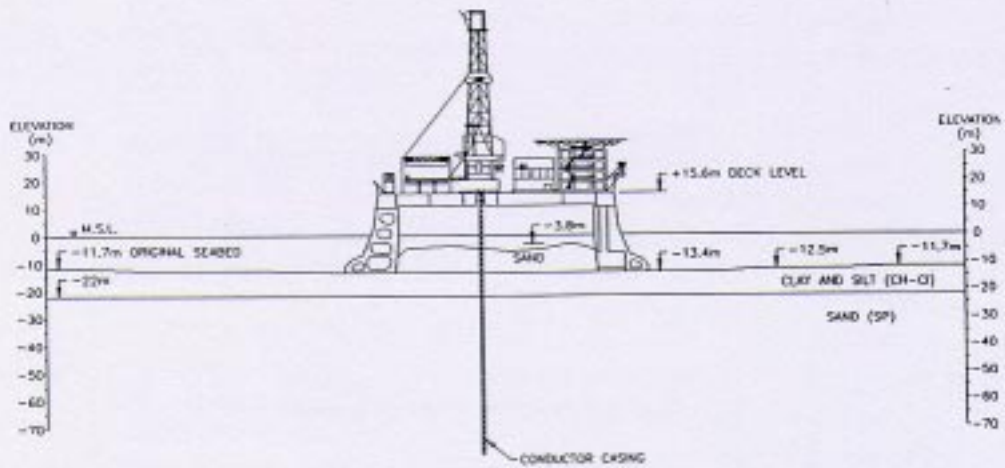


Figure 1.6: Molikpaq at Isserk I-15 1989-1990.

- . **Amauligak I-65** provides a unique data set of various failure modes associated with vertically sided structure interactions in both first and multi-year ice. This deployment provides the dataset of ice loading experience that has been archived on CD-ROM.
- . **Amauligak F-24** early season data provides some interaction event data for sloping walls which may be compared to data from the two previous deployments to quantify the effect of structure slope on the interaction mechanism and failure pressures. The late season data provides information on the effect of grounded rubble ice. However, ice loads are low and the usefulness of the data is limited by measurement resolution because of the low load levels.
- . **Isserk I-15** supplements the database on sloping structure interactions and ice-grounded rubble-structure interactions.

## 1.2 Scope

The scope of work undertaken for this study includes the following key tasks:

- . Existing Gulf Canada reports, operational records and data tapes have been reviewed to identify a representative set of ice events suitable for further research. A listing of the reports on full scale performance monitoring that are archived at the National Research Council of Canada is included as Appendix I. There are sufficient records of ice-structure interactions that filtering out events without adequate completeness of information still leaves many days with good data.
- . Key observations from the four Molikpaq deployments have been summarized. The identified data and reports have been used to illustrate the effect of failure mode on ice failure pressure, for both vertical and sloped ice-structure interactions.
- . A program, DynaMAC, has been written for the widely available and standard MS-Windows environment to read and plot the data tapes transferred from the existing Gulf Canada archive format. This program has some of the functionality of the software originally used by Gulf Canada to analyze ice-structure interaction data, and allows researchers to duplicate previously documented load time series.
- . A database has been built to provide a means of storing the ice documentation from the ice loading events at Amauligak I-65. The program DynaMAC has been expanded to provide a means of accessing this database, information on sensor status and location, and the sensor response data. The database and program have been stored on a CD-ROM for completeness.
- . The results of the study have been presented in a summary report.

### **1.3 Report Structure**

This report has been structured into six sections as follows.

- . Section 1 describes the context and aims of the project.
  
- . Section 2 summarizes the original ice loading criteria developed during the design of the Molikpaq.
  
- . Section 3 introduces the ice-structure interaction data available from the Molikpaq's Canadian Beaufort Sea deployments.
  
- . Section 4 documents the determination of ice loads from the various instrument measurements. This section addresses related issues such as instrument calibrations, resonance effects and the accuracy of the estimated ice loads.
  
- . Section 5 provides an overview of the four Molikpaq's deployments and the data obtained from each season.
  
- . Section 6 discusses the effect of failure mode on ice loads and develops a preliminary failure-mode dependent ice pressure plot.

### **1.4 Authorization**

The work was carried out under contract to Public Works and Government Services Canada, Contract Number XSH94-00025-(405) and XSH95-00089-(406). The Scientific Authority was Dr. Ibrahim Konuk, National Energy Board, and the Contracting Officer was Ms. Dany Carriere.

Information contained in this report is subject to any confidentiality agreements presently existing with Gulf Canada Resources Ltd., the government, and site specific well participants.

## **2. ICE DESIGN CONSIDERATIONS**

### **2.1 General**

In order to operate on a year round basis in the Canadian Beaufort Sea, the Molikpaq was designed to withstand a variety of ice effects. When the original Molikpaq ice design criteria were developed in 1981, there had been a considerable amount of information collected to define the expected range of ice conditions in the Molikpaq's intended area of operations. In addition, some full scale ice loads had been measured on artificial islands in the shallow, sheltered landfast ice zone. However, there was little relevant full scale experience regarding ice effects on the expected performance of deep caisson structures in thick, moving winter ice.

For a design perspective, ice-structure interaction effects are most conveniently considered in terms of global and local ice loads, together with a miscellaneous category that covers areas such as the potential for ice overtopping of the structure, the occurrence of grounded rubble formations around it, and ice scour of the berm. These considerations, together with the Molikpaq's original ice design criteria, are highlighted below.

### **2.2 Global Ice Loads**

Global loads refer to the overall or gross quasi-static and dynamic forces that are experienced by the structure as a result of its interaction with an ice cover. The magnitude of these forces depends upon a number of factors, including the thickness and speed of the level ice, the size and geometry of thicker features such as pressure ridges and multi-year floes that are embedded within it, the overall concentration and make-up of the ice cover, the mechanical properties of the ice, the ice failure mechanisms involved in the interaction, and the environmental driving forces that are available to sustain the ice loads. Global ice loads are of primary importance since they govern the design of the caisson, its berm and its foundation for overall stability.

To develop global ice load criteria for the Molikpaq, the approach taken was to define a number of expected ice-structure interaction scenarios, establish the maximum ice loads for these scenarios and in turn, select the governing design load. These scenarios were subdivided into summer and winter cases and considered in terms of normal and extreme ice loading events. Analyses were carried out from both a deterministic and probabilistic perspective, supplemented with some limited model testing. The ice-structure interaction scenarios that were considered are shown in Figure 2.1 and the associated global load levels used as design criteria are summarized in Table 2.1. Based upon this information, a global design load of 620 MN was selected for the Molikpaq design.

**Table 2.1: Summary of the Original Global Ice Loading Design Criteria for the Molikpaq**

Scenario Description	Deterministic Global Load	
	Tonnes	MN
Multi-year 5 m ice sheet on caisson	70,000	620
Long ridge pushed by pack ice	60,000	530
Short ridge pushed by pack ice	54,000	480
Multi-year hummock floe 8 m thick at 58 cm/sec impact		
normal impact	65,000	580
oblique impact	45,000	400
Embedded floe 5 km in extent pushed by pack	64,000	570
Embedded floe 5km in extent pushed by pack with fully developed free floating rubble field upstream of floe.	56,000	500

Dynamic ice loads can also be a significant factor and refer to the relatively high frequency cyclical variations in load amplitude that can occur. As well the potential for dynamic amplification during impact loading events is important. Cyclical ice loads were an important consideration in terms of the ability of the sand core, berm and foundation to sustain these loads without fatigue and a subsequent loss of strength.

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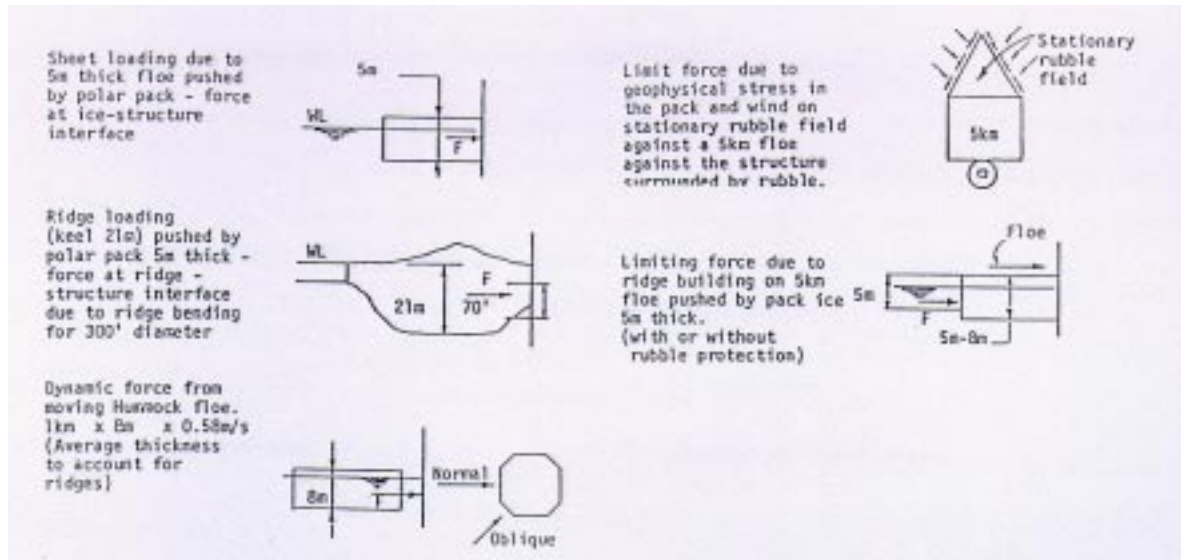


Figure 2.1: Summary of the key ice - structure interaction scenarios that were considered for the Molikpaq's global ice loading design.

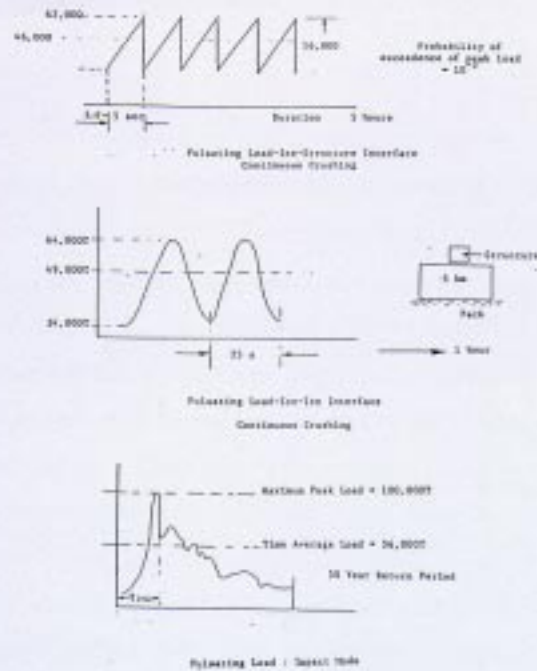


Figure 2.2: Summary of the dynamic ice loading criteria that were used for the Molikpaq's original design work, subdivided by interaction scenario.

Dynamic ice load criteria were a difficult consideration since there was essentially no experience with dynamic loading on deep, wide Arctic structures that were exposed to moving ice. The dynamic loading criteria developed were largely based on judgement and covered pulsating loads that could occur during continuous ice crushing and during thick ice impacts. The dynamic ice load criteria that were defined for the Molikpaq's design are summarized in Figure 2.2, subdivided by the particular interaction scenario assumed.

### **2.3 Local Ice Loads**

Local ice loads reflect the distribution of ice pressures at different locations on the structure and include numerous effects such as the area of ice-structure contact, the degree of confinement in the ice, and its basic strength. Local ice pressures can be much larger than the spatially averaged ice pressure that give rise to global loads over the entire structure and typically decrease as the interaction area increases. Local loads govern the design of the outer shell of the caisson and are important in terms of the steel caisson's structural integrity.

Full scale information on local ice pressures was very limited at the time of the Molikpaq's design as were methods to develop local design ice loads from these pressures. In defining the local loading criteria, it was recognized that local ice pressures vary with area and could be very high over small areas, particularly in thick multi-year ice with high levels of confinement. The local design pressures that were used for the Molikpaq's ice wall are shown in Table 2.2 for the key structural members considered in the design. To estimate local loads, it was assumed that the ice would fail non simultaneously and that areas of high pressure "hard spots" would occur, superimposed on lower background levels of ice pressure. The resultant load criteria were quite complex since they depended on the thickness of the interacting ice feature and the manner in which the structural member that was being stressed distributed the local loads. Table 2.2 provides a benchmark for comparison of design values with local ice pressures measured during the Molikpaq's deployments.

**Table 2.2 - Summary of Local Ice Loading Criteria**

Structural Element or Member Under Design	Local Load	
	3 m above to 9 m below water level	9 m below water level to caisson base
Skin Plate	6.90 MPa	4.83 MPa
Ribs	3.45 MPa	2.07 MPa
Stringers and Intermediate Bulkheads	2.76 MPa	1.65 MPa
Bulkheads and Longitudinal Frames	2.07 MPa	1.24 MPa
Local Edge Load on Webs of all Framing Members	3.45 MPa	3.45 MPa

All local loads are combined with a design stress of 1.38 MPa.

## 2.4 Miscellaneous

There were several other design issues that were not directly related to ice load levels, but rather to the nature of the ice action that the Molikpaq would experience. These considerations included the potential for ice overtopping of the caisson's wall, the possibility of grounded ice rubble forming around the structure, and ice scouring of the berm.

Although the Molikpaq's freeboard was considered to be adequate to prevent any ice overtopping, an outward sloping ice deflector was added at the top section of the caisson's wall to turn back any ice pieces that might reach this level. Field experience with ice pile-ups combined with the results of physical model tests suggested that this arrangement would be adequate. Because of the relatively deep design set down draft of the Molikpaq, grounded ice rubble was not expected to form around it, at least to the extent that it would persist over the course of the winter. However, occasional occurrences of small grounded rubble piles were anticipated and, as noted earlier, design ice loads also checked for this scenario. Some limited ice scouring of the Molikpaq's berm was also expected, but the consequences were considered to be insignificant in terms of the Molikpaq's overall performance. All of these design issues were judgmentally treated during the design phase.

Obviously, there were a number of uncertainties when the Molikpaq ice design criteria were being developed. For the most part, these uncertainties resulted from the fact that there was no large scale experience with deep caissons, and ranged from the ice-structure interaction scenarios and ice failure mechanisms that should be expected, to the ice failure pressures and load levels that would actually be encountered. The ice design criteria that were defined were considered to be conservative at the time but their confirmation awaited the Molikpaq's Beaufort Sea deployment, and the full scale observations and measurements that would be obtained.

### **3. ICE-STRUCTURE INTERACTION DATA FROM MOLIKPAQ**

#### **3.1 Acquisition**

The Molikpaq was comprehensively instrumented and its interaction with ice monitored as part of routine operations. This monitoring accumulated much data on ice structure interaction. Understanding of this information requires an appreciation of the monitoring and data acquisition techniques used. This included:

- some 500 sensors automatically recorded onto tape using a microprocessor system;
- selected manually-read instruments;
- a team of trained people making ice observations;
- low-light time-lapse and hand held video recordings of the ice structure interaction.

Video documentation included both time lapse recordings from cameras mounted on the derrick and the northeast flare boom, as well as portable video recordings. Both types of recordings provide information on failure modes and ice contact with the structure. The time annotation of the time lapse recordings makes it possible to compare structural response concurrent with ice conditions. An example of the video documentation is shown on Figure 3.1.

The onboard ice-observer team was responsible (on a 24 hr basis) for monitoring and documenting meteorological conditions, ice drift, ice thickness and type as well as ensuring the data acquisition system was operational. During significant ice interactions with the Molikpaq, the ice team documented the event in real time. Event observations included ice type, ice thickness, drift speed, failure modes (crushing, buckling, cracking, and flexure), ice contact factors, rubble formation and so forth. An example of the documentation produced by the ice observers is presented on Figure 3.2. Onboard monitoring was supplemented by various forms of imaging and occasional on-ice surveys.

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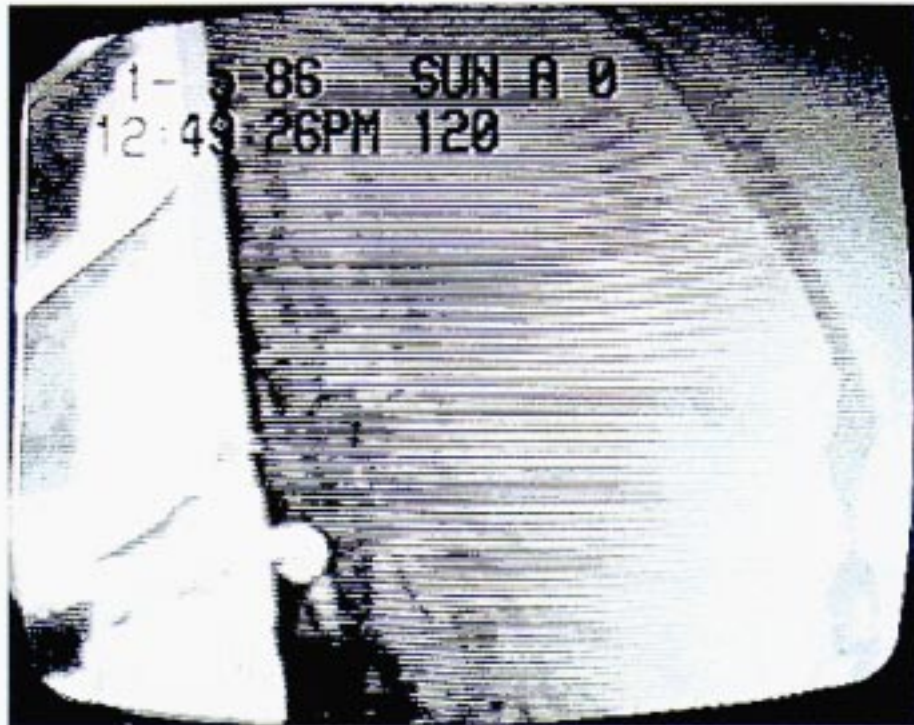


Figure 3.1: Example of video documentation of ice-structure interaction.

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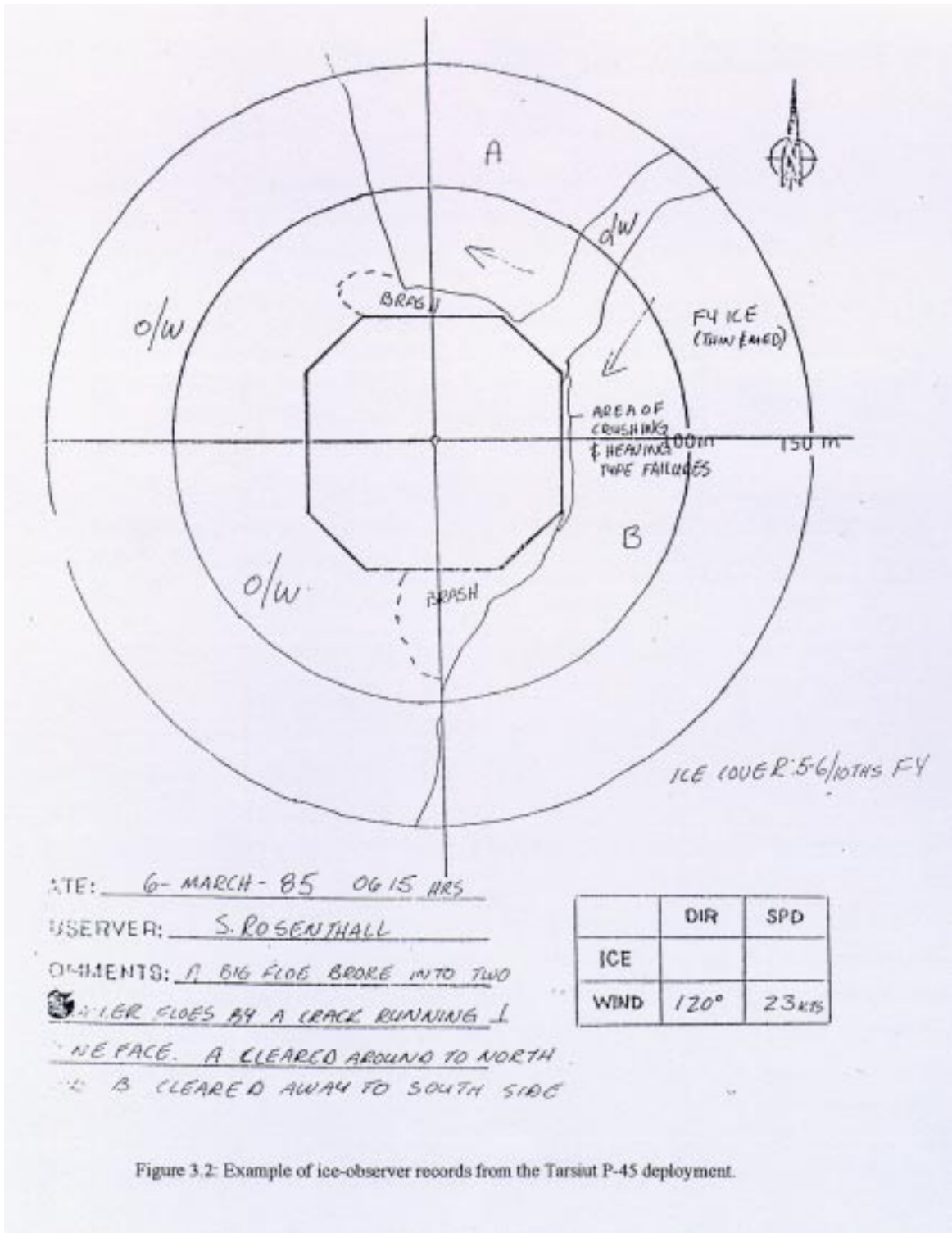


Figure 3.2: Example of ice-observer records from the Tarsiut P-45 deployment.

A description of the instrumentation system in place in 1984 has been described by Rogers et al. (1986) in a paper titled "Performance monitoring of the Molikpaq while deployed at Tarsiut P-45", 3rd Canadian Conference on Marine Geotechnical Engineering, St. John's, Newfoundland. The instrumentation is summarized in Table 3.1.

**Table 3.1 - Summary of the Molikpaq's Instrumentation System at Tarsiut P-45**

Type of Instrument	Location	No.	Range	Resolution	Function
Medof Ice Panels	Caisson N, NE, E - Ice Faces	30	0-2000 Tonnes	1 Tonne	Ice Loads and Pressures
Strain Gauges	Caisson N, NE, E - Ice Face - Bulkheads - Sand Face - Base	60 168 24 30	±4140 ms	2 ms	Steel Strain and Stress
Extensometers	Caisson/Deck/Conductor Pipe	10	± 184 mm	1 mm	Caisson Deformations
Accelerometers	Caisson Core	18 2	±50% g	.025 % g	Tilt and Dynamic Response
Water Level Gauges	Ballast Tanks & Draft Levels	16	30 m	0.05 m	Water Levels
Total Pressure Cells	Caisson Base	40	± 3450 kPa	2 kPa	Base Contact Pressures
Piezometers	Caisson Sand Face Sand Core & Berm Foundations (Manual)	2 35 46	0-1035 KPa	1.7 kPa	Pore Water Pressures
Inclinometer	Core, Berm, Foundations (In-Place) Core, Berm, Foundations (Manual)	24 6	±2.5 Deg.	.002 Deg.	Lateral Deformation
Temperature Sensors	Medof Panels, Core, Berm	5 2	±100°C	.1°C	Temperature
Video Cameras	Derrick Top, NE Flare Boom	4	-	-	Film Documentation

The majority of the instruments on the Molikpaq were monitored using an automated data acquisition system. The manually read instrumentation primarily comprised the inclinometer system which was used to document residual movement of the Molikpaq after an ice event. The time required to read this system, half a day for a full set of readings, precluded its use in monitoring load-deflection relationship of the core during the ice-structure interaction. The system was read weekly and after significant ice events to give a record of any permanent movement of the platform. The other manual instruments were the piezometers used to monitor the long term behaviour of the foundation.

For purposes of monitoring ice load, four types of the automatically read instrumentation were used as follows:

- . direct measurement of local ice load (Medof panels);
- . indirect measurement of ice load (bulkhead strain gauges);
- . indirect measurement of face load inferred from caisson ovaling, or caisson movement relative to the centre guide pipe (extensometers);
- . measurement of dynamic response (accelerometers).

Determination of the ice load from these sensors is described in the next section. However, it is first necessary to understand the data acquisition system, in particular what was recorded and how.

Selection and configuration of a suitable industrial quality data acquisition system was undertaken jointly with Hewlett Packard Ltd. The electronic monitoring used a Hewlett Packard 9920 microcomputer in tandem with two Hewlett Packard 6944 multiprogrammers. Scan data was initially stored onto 15 MByte hard discs which were backed up onto DC600 tape cartridges. The hard discs configured in 1984 were the largest available for microcomputer based systems and it was this maximum stored data limit that determined how the data acquisition was configured.

Three modes of data acquisition were used to obtain the required information while remaining within the limit of the system. These modes were:

- . slow scanning (3 minute average, maximum and minimum on all channels);
- . fast scan rate (1 to 10 Hertz scanning of all channels);
- . burst scan rate (50 or 75 Hertz scanning of a key sub-set of channels).

The platform response was the principal determinant for which mode was used. Slow scanning was used for normal operations. Accelerometer and extensometer output were used to trigger a fast or burst scan rate if the thresholds input by the monitoring team were exceeded. Mode control was carried out by the HP 9920 computer and a rolling buffer scheme was used so that a few seconds of data leading to the trigger event was recorded as well as the post trigger period. This faster scan data was key to documenting the dynamic response of the Molikpaq.

The burst file was limited to a 90 second block, and allowed a "snapshot" of a particularly dynamic response sequence. Furthermore, if the dynamic response became larger during the event then a quasi-continuous record (to the limit of the storage media) was obtained.

The fast scan ran in parallel with the burst scanning. However, as the fast scan is typically 1/50th of the rate used in the burst system, much longer scan durations were possible even though more transducer channels were being recorded. The limitation of the fast scan system was its inability to resolve the nature of the platform dynamics. It did, however, capture information related to the quasi-static loading.

## 3.2 Terminology

Local ice loads were estimated using Medof panels and strain gauges positioned at several discrete locations around the Molikpaq, and these unit loads were then integrated along the length of the respective face to give the overall loads.

Thus, it is possible to provide three expressions of load:

- local loads at each sensor group or individual sensor;
- face loads;
- global loads.

As illustrated on Figure 3.3, the primary load information is derived from three Medof panel groups on the north and east long faces respectively and one Medof panel group on the northeast short face. The loads from any of these seven groups can be treated as a local load, and it is the comparison of these local load synchronizations that allow issues such as non-simultaneous or phase-locked failure to be addressed from measurements.

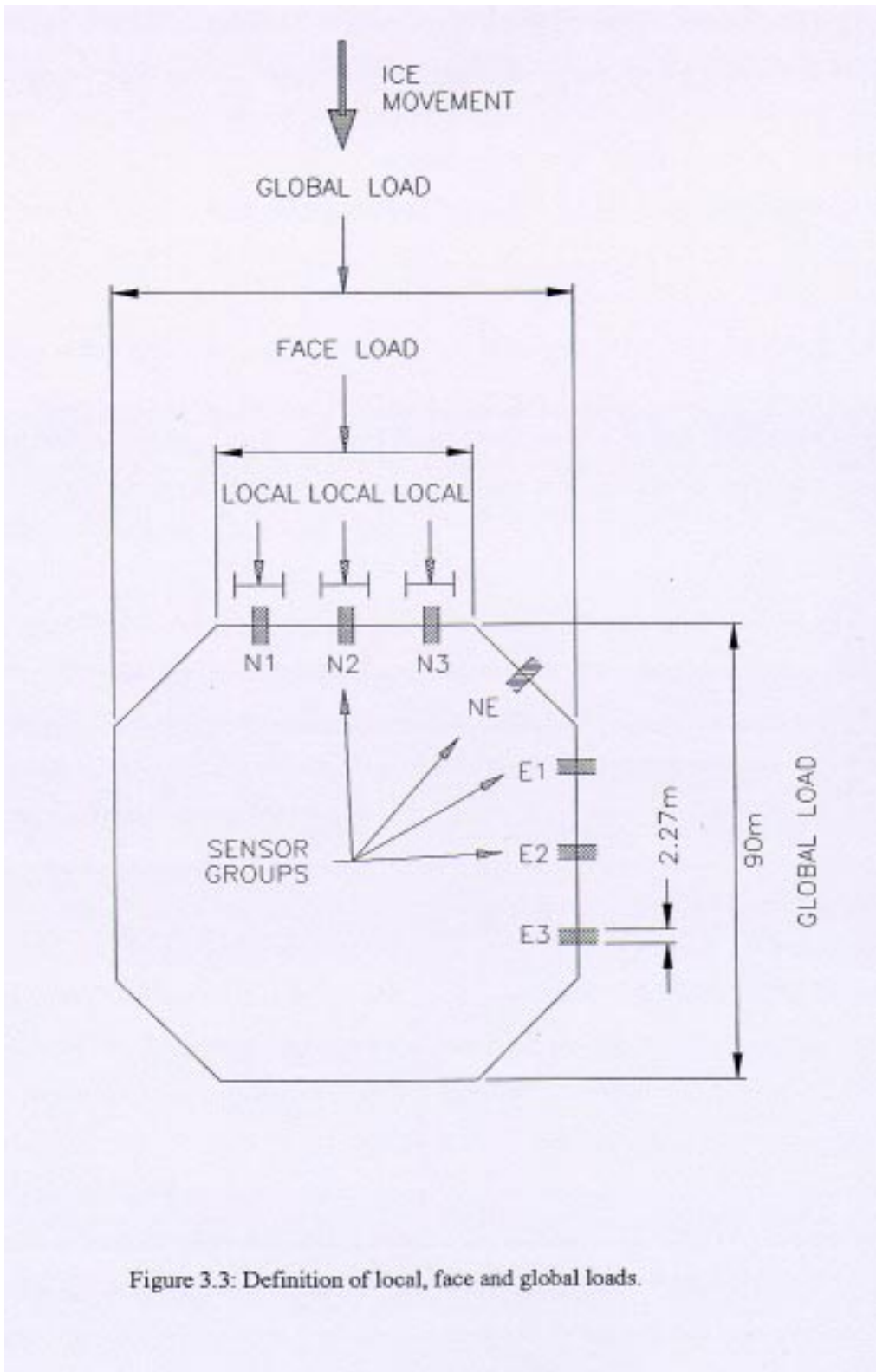


Figure 3.3: Definition of local, face and global loads.

Each Medof panel sensor group has a sensing width of two panels, each 1.135 m wide. The long face of the Molikpaq at the operating interlines is approximately 60 m, and so the coverage of the sensing groups is about 10% of the long face. Face loads are estimated by assuming that the pressures measured by each group correspond to the pressures acting over the adjacent part of the face; comparison of the synchronization between each of the three sensor groups and load variation experienced by each allow determination of the uncertainty inherent in the calculated face load because of the assumption.

Face loads are less than global loads, global load being the total force exerted by the ice as it moves past the Molikpaq. Basically, the Molikpaq cuts a path at least 90 m wide as ice moves past the structure. Global loads are determined by vector summation of corner and face loads, or can be based on multiplying the face load by a factor based on the actual interaction width to measured width.

A review of ice event documentation on the Molikpaq indicates that there are many uncertainties in the estimation of global loads, so it is recommended that ice/structure interaction research on ice failure pressures using the Molikpaq data set is best limited to loads and load distribution along the long faces, equivalent to what Gulf Canada Resources Ltd. have referenced as face loads.

Within the concept of ice load, it is also important to appreciate that ice load varies with time. There are several scales of time variation, and the ideas behind these time-related variations affect what is meant by "maximum" or "peak" load. The various ideas and corresponding definitions have been summarized on Figure 3.4. As indicated, failure mode is an important factor when discussing load-time series.

### **3.3 Failure Modes**

A wide variety of ice failure mechanisms were observed when the Beaufort Sea's pack ice cover moved against the Molikpaq, often in apparently similar ice conditions. These ice failure mechanisms are very important and are reviewed first, since they determine the magnitude and distribution of the ice pressures that the ice cover exerted and, in turn, govern the ice loads and Molikpaq responses that resulted.

The most important and frequently occurring failure modes that were actually observed during the Molikpaq deployments included crushing, bending and buckling of level ice, which sometimes occurred as pure or singular failure mechanisms, but more often as a combination of mixed modal ice failures. Other interaction mechanisms that were observed included the large scale fracture of first, second and multi-year ice, rather complex pressure ridge failures, and the formation of floating, temporarily grounded and grounded ice rubble. Since the ice loads and Molikpaq responses experienced were directly related to these ice failure modes, they are described in more detail as follows:

### Crushing

Although some ice crushing with the Molikpaq was expected, the most surprising observation from Tarsiut P-45 and Amauligak I-65 was the extent of the continuous crushing that actually took place during an event, often across the entire width of the caisson. This type of ice failure behaviour had been considered in the original ice design criteria but had never been observed on such a large scale and over such substantial widths. Figure 3.5 shows a typical example of level ice crushing against the Molikpaq, with compressive ice failures localized at the caisson wall. This crushing process resulted in granular, powder like ice rubble across the interaction front, part of which was piled on top of the oncoming ice sheet, with the remainder pushed beneath and/or cleared around the caisson corners. The lateral extent of the crushed ice zone sometimes covered the entire width of the caisson but more often occurred across shorter portions of its face, frequently in combination with other failure modes. After some crushing had occurred and crushed ice debris had built on top of the moving ice cover, the oncoming ice sheet normally collapsed because of flexural failures away from the caisson wall. With this type of sudden flexural ice failure, the crushing ice loads would drop suddenly, sometimes resulting in accelerations that could be felt on the structure. With continued ice movement, flexural failures would continue at the rubble boundary for a short time period, then the intact ice

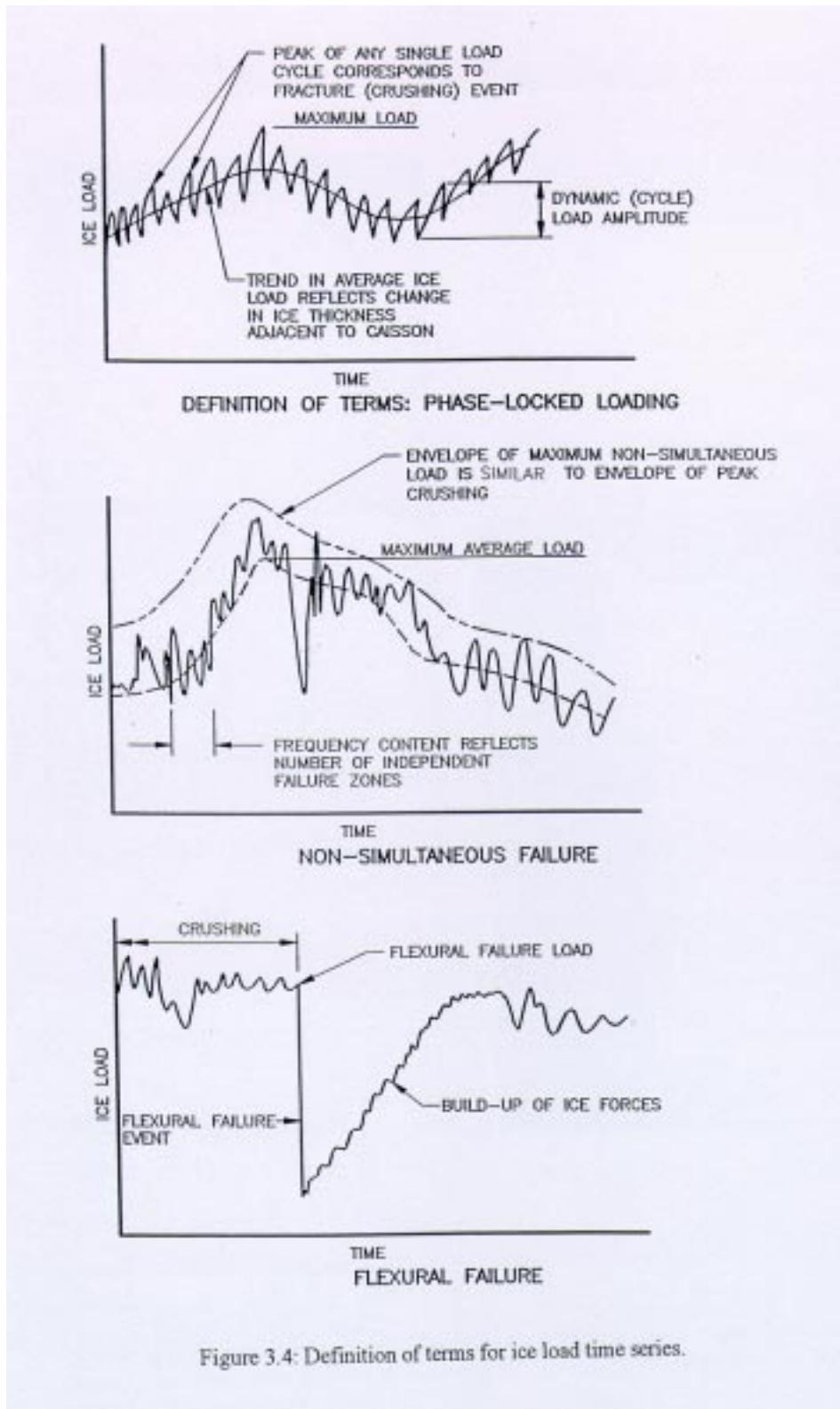


Figure 3.4: Definition of terms for ice load time series.

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Figure 3.5: Representative examples of ice crushing. The top figure suggests non-simultaneous crushing while the lower figure is characteristic of crushing with pulsating loads. In this case a paste-like ice extrusion is evident.

sheet would penetrate the rubble and resume crushing, followed by a repetition of the cycle. During these ice crushing events, the ice loads experienced by the Molikpaq were high in comparison to those associated with other ice failure behaviours. Figure 3.6 shows ice load time series records that was acquired over the course of an ice event on the North face. Generally, the ice-structure interaction zone where crushing was occurring was quite even. However, ice crushing did not necessarily imply a uniform ice pressure distribution across the caisson face, since variations in ice thickness and strength still appeared to lead to non-simultaneous crushing failure behaviour at different locations.

On a number of occasions, however, particularly at relatively low drift speeds, ice crushing failures appeared to occur in a pulsating or cyclic manner with failure frequencies ranging from between 0.5 and 4 Hz. Although not well understood, it was felt that this failure behaviour was the result of the ice crushing failure mode acting in combination with the elasticity of the ice sheet. These pulsating ice loads were synchronized across the caisson face and corresponded to the highest load levels for a given ice condition. Ice induced vibrations of the structure typically persisted for the duration of the cyclical crushing event. This type of failure behaviour has been referred to as simultaneous or phased locked crushing.

Crushing is the failure mode that consumes the greatest amount of energy and generates the highest ice load levels. However, nature favours other ice failure mechanisms that require less energy and these tend to result in lower load levels for the same ice conditions. In terms of occurrence, a variety of other ice failure modes and interaction behaviours were observed more frequently, during the winter season which led to normal global load levels that were quite low.

### Flexure

Flexural failure of the ice sheet was quite common, particularly in thin ice moving at moderate to high speeds, and took place when the leading edge of the oncoming ice cover was bent either upwards or downwards. Depending upon the ice thickness and to a lesser extent, the ice speed, flexural ice failures were initiated in one of two ways. As shown in Figure 3.7, thin ice sheets often bent up or down, depending upon the configuration of broken ice adjacent to the caisson wall. This resulted in ice pieces of variable size and often led to the formation of floating rubble piles that moved the ice failure zone away from the caisson wall. The second type of bending failure involved downward flexural failure of

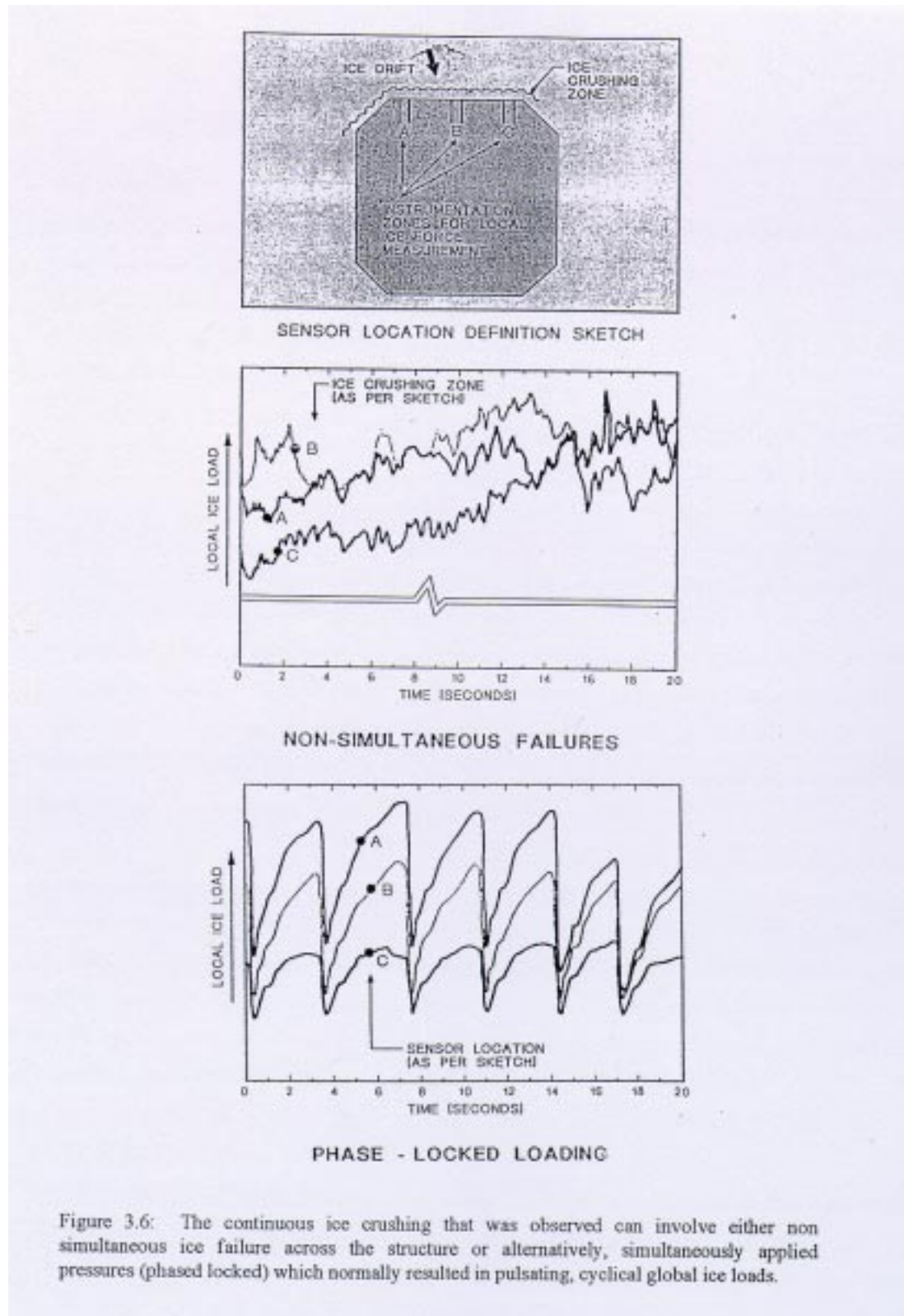


Figure 3.6: The continuous ice crushing that was observed can involve either non simultaneous ice failure across the structure or alternatively, simultaneously applied pressures (phased locked) which normally resulted in pulsating, cyclical global ice loads.

the oncoming ice sheet that was initiated by the weight of crushed ice debris, as described earlier. This second type of flexural failure was more typical when the ice was thicker and drift speeds were slower. Often, flexural cracks were observed to form across the entire width of the caisson, followed by a sudden collapse of the ice sheet and a reduction in ice load.

### Buckling

Buckling was quite common, and was most frequent when the ice was thin. This type of ice failure was usually observed across limited widths of the interaction front and often resulted from an eccentricity in the leading edge of the ice sheet. An example of buckling is shown in Figure 3.8. Buckling normally involved failures that were sudden and resulted from instability due to excessive in plane stresses. However, creep buckling was also a frequent failure mode at very low drift speeds which lead to a lower apparent modulus of elasticity.

### Mixed Modal

The vast majority of the ice interactions with the Molikpaq involved a combination of two or more of these failure modes, occurring simultaneously across different parts of the loaded caisson wall as illustrated in Figure 3.9. Combinations of flexural, buckling and crushing failures resulted in an averaging of different pressure levels across the interaction front and loads that were low in comparison with continuous crushing.

### Large Scale Fractures

Under certain conditions, instead of ice failure immediately adjacent to the caisson wall, cracks propagated away from the Molikpaq, anywhere from tens of metres to several kilometres into the oncoming ice cover. An example is shown in Figure 3.10. This tended to be most common in cases of low confinement in the surrounding pack ice cover, such as the impact of individual ice floes, separated from each other by open water or large leads. Cracking and large scale fracturing was favoured during periods of high ice drift speeds when the ice behaved in a more brittle manner and in thick, non uniform ice conditions. The loads associated with this type of failure behaviour were relatively low. Sometimes, cracking would follow periods of high ice loading events and there would be a rapid transition, and a sudden reduction in load levels.

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Figure 3.7: Typical examples of flexural ice failures. The upper figure shows bending failures at the ice sheet's leading edge, while the lower figure shows downwards bending due to the weight of the rubble debris at the caisson wall.

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Figure 3.8: Typical examples of buckling. The upper figure shows creep buckling while the lower figure shows flexural buckling that was common at higher ice interaction speeds.

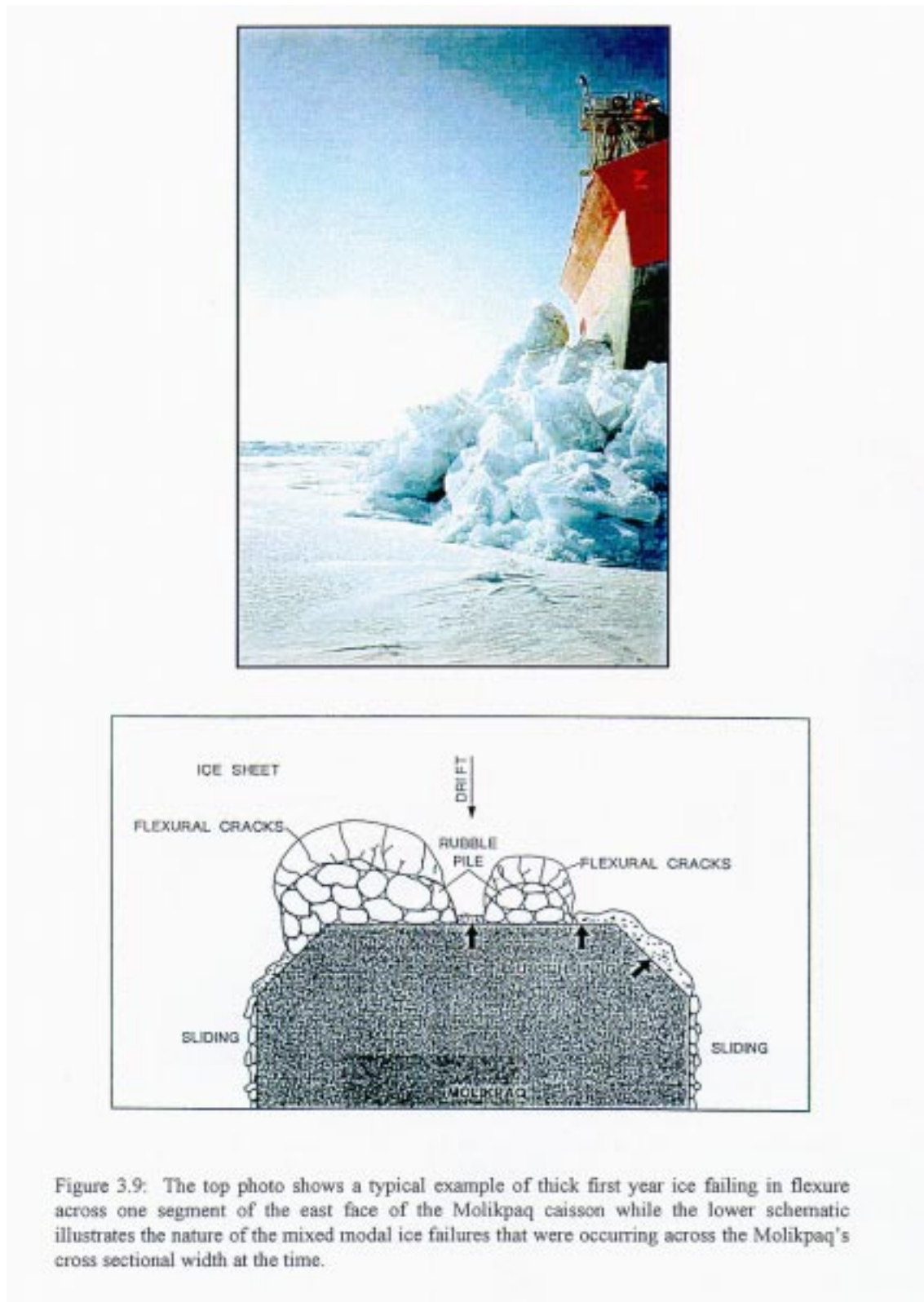


Figure 3.9: The top photo shows a typical example of thick first year ice failing in flexure across one segment of the east face of the Molikpaq caisson while the lower schematic illustrates the nature of the mixed modal ice failures that were occurring across the Molikpaq's cross sectional width at the time.

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Figure 3.10: Typical examples of large scale fractures propagating out from the Molikpaq's ice interaction front. The top photo shows a number of cracks that in this case were associated with bending ice failures against floating rubble debris adjacent to the caisson wall, while the lower photo shows a crack that formed off one of the caisson's corners and has opened into a small lead. Often, cracks were observed to form at the corners between the Molikpaq's long and short faces and propagate out into the oncoming ice cover.

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Figure 3.11: Typical examples of ice rubble that formed off the Molikpaq caisson. The upper photo shows a floating rubble formation while the lower photo shows a grounded rubble pile. When the Molikpaq's deployment draft was deep, the occurrence of grounded rubble piles was very rare and they would be swept away by subsequent ice movements anywhere from a few hours to a few days after they had formed.

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### Rubble

In most cases, the rubble caused by ice failure tended to quickly clear around the structure, aided by the current flow around it. However, large temporary rubble piles sometimes formed on the upstream side of the Molikpaq, as shown in Figure 3.11. These pile-ups tended to occur when the ice was moving perpendicular to one of the long faces of the caisson. These pile-ups were most common when the ice was more than 0.5 m thick with no cracks or leads in the oncoming ice cover to disrupt the continuity of rubble formation. The dominant failure mode observed during these pile-up events was flexural failure at the floating rubble boundary, either upwards or downwards. The ice pressures and loads on the caisson walls during pile-up events were typically low.

Rubble piles sometimes extended down to the caisson toe and often had significant freeboards or sail heights. On one occasion at Tarsiut P-45, ice in the sail of a rubble pile extended to the height of the deflector (+14 m above MSL) and some blocks overtopped the caisson wall near the middle of the long face. However, the deflector was generally very effective in turning back ice blocks pushed up to its height. On two occasions, the submerged portion of large rubble piles grounded on the berm and remained stable adjacent to the Molikpaq for several days before being swept away by ice movements along the caisson face.

At Amauligak F-24 and Isserk I-15 the Molikpaq was set down at a shallower draft, and permanent accumulations of rubble ice formed around the caisson, lasting until break-up.

### Frozen-in Condition

During long periods of static ice conditions, there was some speculation that there might be bonding or adfreeze between the structure and the ice, leading to relatively high break-out loads. However, truly static ice conditions do not actually occur in the offshore Beaufort Sea because of small but real ice movements, tides and other water level changes, and this frozen-in adfreeze condition was never observed.

### Pressure Ridges

A considerable number of first year pressure ridges interacted with the Molikpaq over the course of the 1984/85 and 1985/86 seasons. Most of these ridges were small to moderate in terms of their overall thicknesses (5 to 10 m including their sails and keels). A few were relatively large with total thicknesses approaching 15 to 20 m. These ridge interactions were characterized by a wide variety of failure behaviours that to a large extent, were "new" since no similar observations had been obtained before. Ridge failure mechanisms included bending failures down the spine of the ridge sails, failure of the level ice in the parent ice sheet behind them, shearing of some of the ridges, or ridge stopping and then fracturing into a number of individual segments across the width of the caisson. Although the global ice loads that were associated with these first year ridge interactions were not particularly high in comparison to the loads from the parent ice cover, there was normally an increase in ice load levels as first year ridges moved past the Molikpaq.

However, the ridge failure forces were typically not as high as those pressures associated with simultaneous crushing of the level ice cover.

Molikpaq also experienced interactions with multi-year flows which included hummocks and pressure ridges during March-April 1986. These interactions were the trigger for the joint industry dynamics project initiated by Gulf Canada Resources Ltd. to study the ice events from the Amauligak I-65 deployment.

## 4. ICE LOAD MEASUREMENT

### 4.1 Systems Used

As introduced in Section 3, ice loads were monitored using four transducer systems:

- Medof panels mounted on the exposed face of the structure directly at the ice-structure interface;
- strain gauges mounted on the bulkhead struts supporting the external face of the caisson at the waterline;
- extensometers mounted between the annular caisson and the box girder deck;
- accelerometers mounted in the caisson, and in the centre of the sand core.

It should be appreciated that the transducer systems evolved over time, and that each system covers different aspects of the ice load documentation. It is recommended that the four transducer systems should be used in a complimentary manner to provide the best estimates of load level and loading frequency.

Each of the transducer systems are described in turn below. Drawings documenting the location of the sensors at the Amaulikak I-65 deployment are included in Appendix II.

#### Medof Panels

Thirty one ice load (“Medof”) panels were installed on the north, northeast and east faces of the caisson when the Molikpaq was built to provide a direct measure of ice load. Historically predominant loads were expected to occur from these directions. The panels were arranged in 7 clusters of 4 or 5 panels. Temperature sensors (RTD's) are embedded into the caisson outer plate directly behind several of the panels, which allow thermal corrections to be made. Caisson loads are determined by integrating the measured ice loads across the face using the ice contact factors as observed on the video or by ice observers.

Although the ice load panels provide a direct measure of ice load, they have a limitation in that the response time to a step change in load is in the order of 5 to 10 seconds. They are, therefore, inaccurate for the measurement of cyclic ice forces with fundamental frequencies in the range 0.5 to 3 Hz. However, the Medof panels do sense the average load during these cyclic load events.

### Strain Gauges

The rapidly fluctuating (dynamic) ice loading was measured by strain gauges. Over 200 strain gauges were installed during Molikpaq construction on the north, northeast and east segments of the caisson covering locations on ribs for the ice and sand faces, and the base plate, and on the main and intermediate bulkheads. These gauges were located to monitor the resultant stresses in critical locations on the structure during periods of ice interaction. Experience with the response of these strain gauges showed that those referenced as the '09 series' had the best sensitivity and linearity for the load measurement of ice up to 5 metres thick. Therefore, additional '09 series' gauges were installed on the Molikpaq in April, 1986 to give coverage at sixteen main bulkhead locations around the structure.

### Extensometers

An uncertainty with both Medof panels and strain gauges is that they monitor local loads, typically within a tributary area of a few metres. Because of the requirement to extrapolate local data, the extensometers were also used to infer face/global loading. The Molikpaq has complex load paths but broadly can be idealized as a proving ring (the annular caisson) with an internal stiffening spring (the core). As ice loads are applied to the Molikpaq, the annular caisson deforms in an oval manner and this ovaling was sensed using pairs of extensometers. A total of eight (8) rod extensometers are mounted at deck level at the midpoint of each caisson sides to monitor movement between the caisson annulus and the box girder deck. Two (2) additional extensometers were mounted in the drill collar of the box girder deck to monitor movement of the deck relative to the conductor casing to provide a measure of absolute caisson deformation.

A limitation of the extensometers as a method of estimating ice loads is that, although the extensometers have excellent frequency response, the parameter being sensed (ovaling) is in fact a caisson behaviour and as such is affected by caisson motion during dynamic events and by the interaction of ice on other faces of the caisson. The calibration also assumes that the sandfill stiffness does not change during the ice load event.

### Accelerometers

Platform response to ice load was also monitored by accelerometers. Sixteen (16) biaxial accelerometers (eight "tiltmeters") were mounted at deck level in each of the caisson sides to measure dynamic response and overall caisson tilt. Four (4) additional pairs of biaxial accelerometers were installed near the base of the caisson in pump or valve rooms in the centre of each long side. In the centre of the core space a triaxial and biaxial accelerometer set were located at the top of the core surface, and in a bore hole near the base of the caisson, respectively. The response data from the accelerometers were used to assess the structure and sandfill response to loading.

## **4.2 Calibration**

Considerable work was undertaken over several seasons to calibrate the ice load transducer systems. Although there are many calibration and testing reports to be found in the Gulf Canada files, three documents in particular summarize these efforts and should be referenced for a more complete understanding:

- . Dynamics Project, Phase 1b- Volume 1, Section 3 and Section 4;
- . Dynamics Project, Phase 1b- Appendix A; Detailed Review of Medof/Strain Gauge Calibration
- . Dynamics Project, Phase 2 - Volume 2: Load measurement on the Molikpaq.

The calibration work on Medof panels was carried out before the panels were installed, with additional testing undertaken in the laboratory after the April 1986 ice loading events. Further, particular care was taken to establish and model the creep behaviour of these Medof panels. Therefore calibration of Medof panels is traceable back to individual dead load tests carried out in a laboratory setting.

Strain gauges are an indirect measure of force and it is necessary to know the load paths in the structure and their relative stiffness before ice load can be properly determined from steel strain. Four approaches were adopted:

- . calibration against the ice load Medof panels during static creep ice events without any dynamic loading - in effect a field dead load calibration;

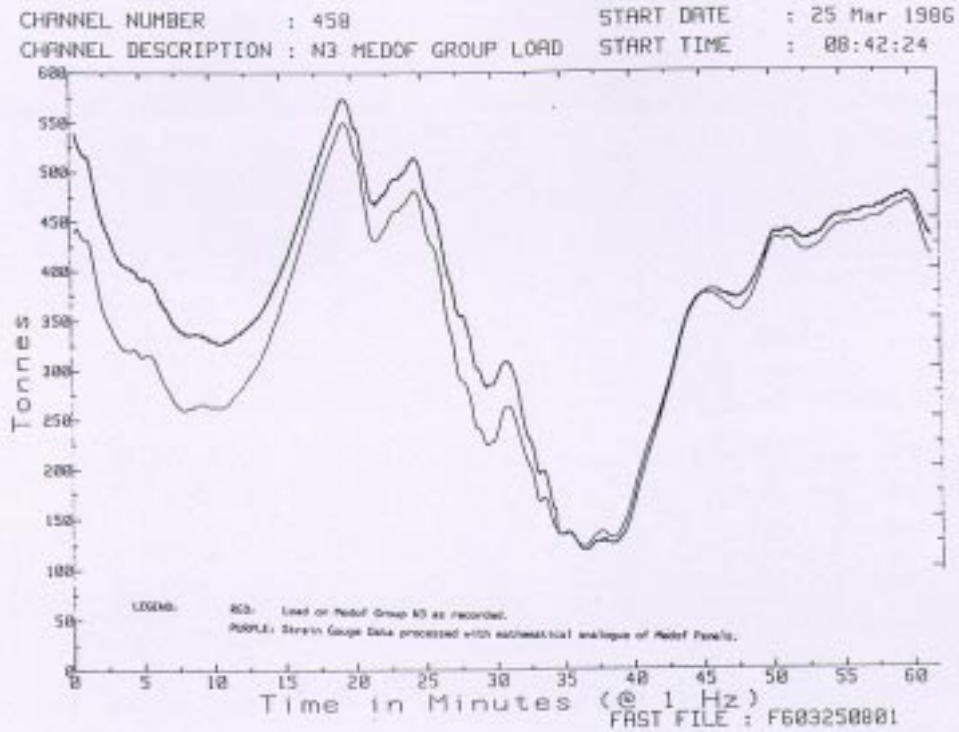
- . calibration against the ice load panels during ice load events using a five-element model of the ice load panel behaviour;
- . dead load calibration by deballasting the ballast tanks and the use of hydraulic jacks;
- . finite element modelling.

Examples of the '09 series' strain gauge calibration against the Medof panels is illustrated on Figure 4.1 for a creep and a dynamic load event. Excellent correspondence is evident. Also shown on Figure 4.2 is the Medof response during a dynamic load event, from which it can be seen how the Medof panel response causes under-reading of ice fracture peak loads by about 30%.

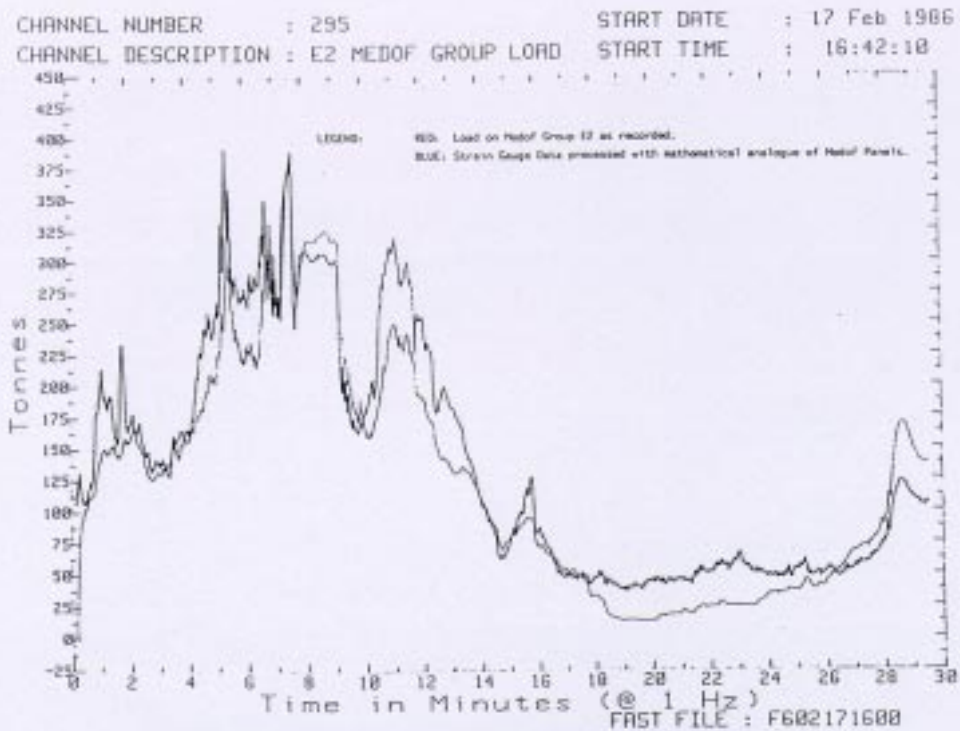
Dead loads were put on the bulkhead struts by ballasting and deballasting the tanks. This was particularly useful to calibrate the relative response of the various bulkheads with '09' gauges as the gauges response was different depending on the amount of other steel adjacent to the bulkhead. The differences in gauge factor are significant and must not be neglected by using an average gauge factor for all bulkheads to compute ice loads.

Finite element modelling was used to understand gauge response and in particular explore the response of gauges to ice thickness. Figure 4.3 summarises the results of the finite element studies in terms of effective gauge factor, and compares the calculations with factors inferred from calibration against the Medof panels. For the regular bulkheads there is reasonable agreement for ice thickness in the range 1 m to 5 m; for thinner ice, the calibration against the Medof panel suggest gauge factors should be stiffer.

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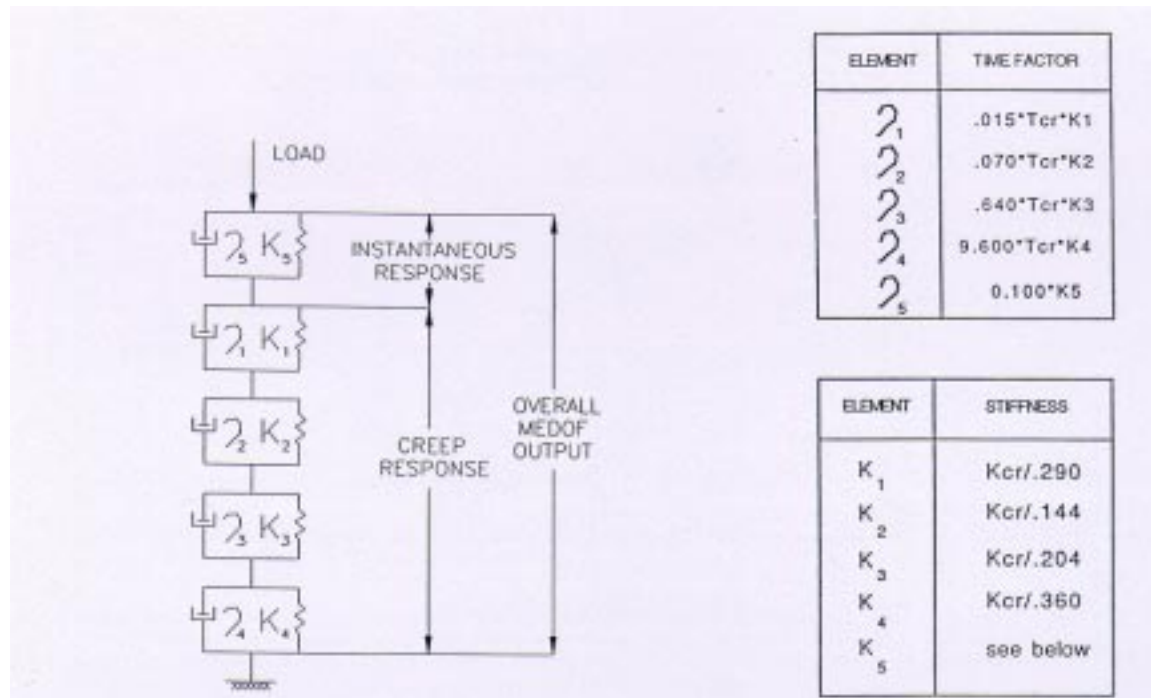
(a) Comparison for March 25, 1986 - 2m thick ice



(b) Comparison for February 17, 1986 - 0.5m to 0.8m thick ice

Figure 4.1: Strain gauge calibration against Medof Panels.

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Note: See Table 2.1, Phase 1b: Appendix 'A' Individual values of  $T_{cr}$  and  $K$

Mathematical analogue of Medof Panels

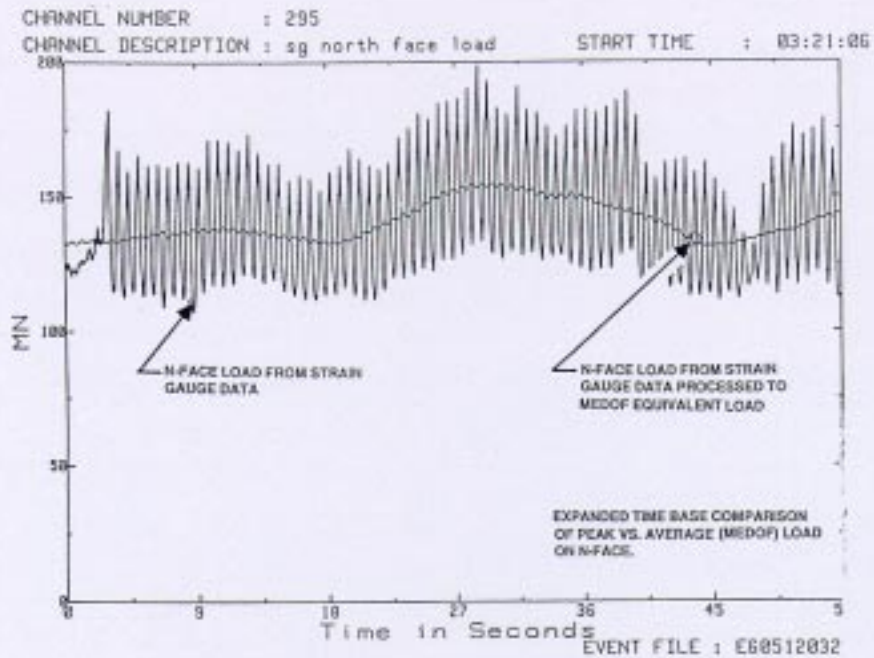
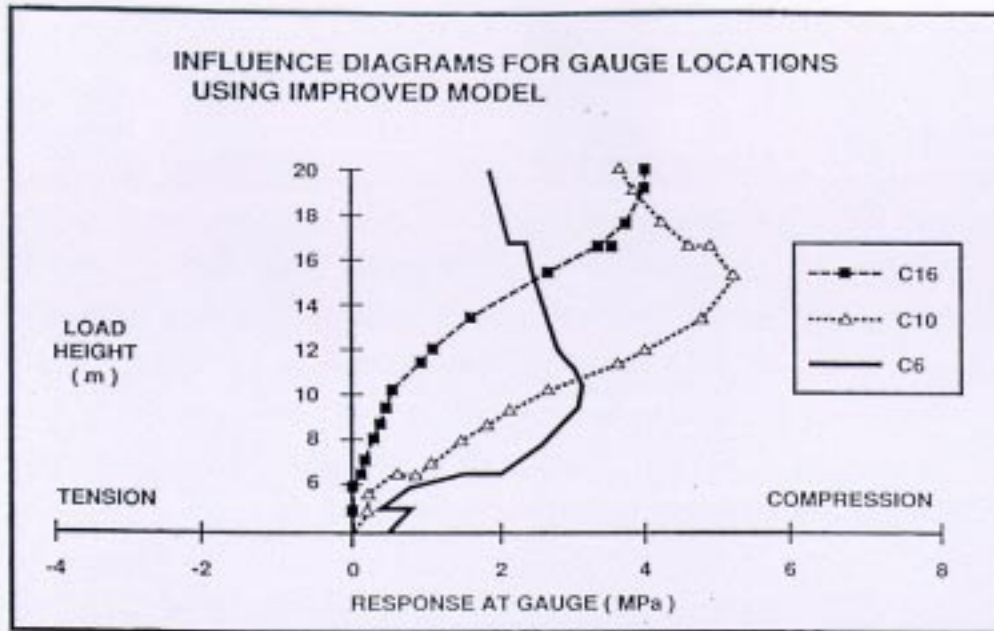


Figure 4.2: Strain gauge calibration against Medof Panels.

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Artec Canada Ltd. FEM results

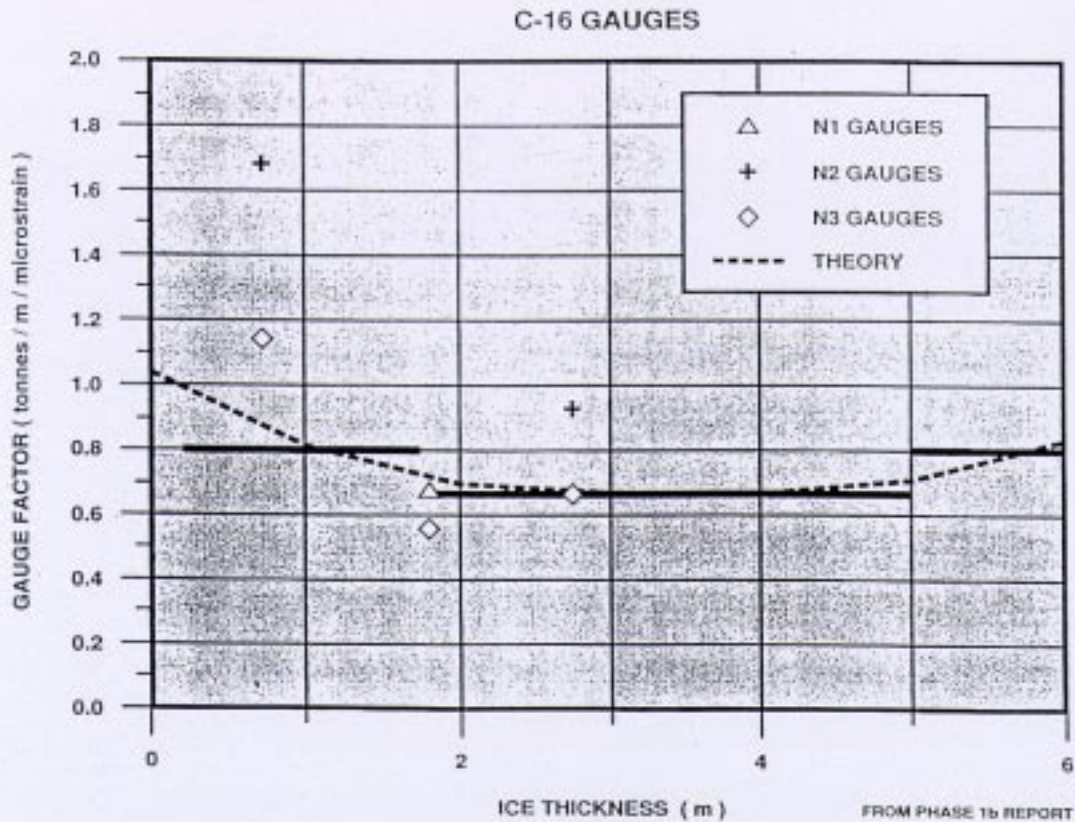


Figure 4.3: Effect of ice thickness and point load application on strain gauge calibration factor.

Based on the calibration work, the Molikpaq analysis typically used a constant gauge factor for each bulkhead for ice thicknesses up to 5 m. This approach is pragmatic and necessary because there was no real time monitoring of ice thickness. The approach has the effect that ice loads estimated from 09 series strain gauges may be too low for ice thicknesses less than 1 m and greater than 4 m. Strain gauge factors used as the default values in the DynaMAC program are documented in Table 4.1.

### 4.3 Accuracy

The accuracy with which ice loads can be determined from the sensor measurements made on the Molikpaq was analyzed and reported within the dynamics project. Broadly, the results of this work can be summarized as:

- face loads can be estimated to a precision of  $\pm 20\%$  to  $30\%$ ;
- local ice loads can be estimated to a precision of  $\pm 10\%$ .

**Table 4.1 - Reference Strain Gauge Factors Used in DynaMAC**

Sensor Name	Bulkhead #	Gauge Factor kN/2.44 m width/microstrain
N1	311	24
N2	327	30
N3	13	22
NE	39	24
E1	65	24
E2	81	30
E3	101	24
SE	123	22
S1	147	24
S2	161	30
S3	183	24
SW	207	22
W1	229	24
W2	245	30
W3	265	24
NW	287	22

Note that it is loads, not ice pressures, that are determined by the measurement systems. Thickness measurements are required to establish ice pressures. These measurements were not usually made, and ice thickness estimates had to be determined from video and visual observations.

The dynamics project used sensor response data and ice structure interaction models to assess the effect of possible structure resonance on the measurement of ice loads on the Molikpaq. This is reported in the Phase 1b dynamics project which concluded that:

- very large damping (typically about 20% of critical) was associated with dynamic loading;
- the frequency range of observed dynamic interactions was far too large for the hypothesis of resonant induced excitation to be correct;
- ice loads at the ice-caisson interface derived from strain gauges might be affected by neglected inertial terms during dynamic loading equivalent to an error of  $\pm 2.5\%$  in reported load;
- the ice load seen by the foundation may be different from the ice load applied to the caisson because of inertial effect. This changes from event to event and is ice-condition specific. The estimated ratio of foundation load to applied load varied from slight amplification during part of May 12, 1986 to slight attenuation on April 12, 1986.

Use of the dynamic ice structure interaction models must recognize the effect of the nominal 10 Hz anti aliasing filters installed on the Molikpaq during construction. These filters were later tested by Arctec Canada Ltd., and found to be equivalent to 4 Hz filters which will have distorted some of the recorded accelerometer data.

The problem of severely over-filtered data was handled within the analytical work carried out by setting up digital filters to simulate those onboard the Molikpaq. Computed signals were passed through the digital filters before comparing the results of computations with measurements. This approach is discussed in detail in Appendix G of the Phase 1B Dynamics Project report, and an example of under-reporting of accelerometer data can be found in the Volume 1 (Figure 9.50) of the Phase 1B Dynamics Project.

As only one set of filters were used at Tarsiut P-45 and Amauligak I-65, it also follows that the filter frequency was too high to anti-alias the fast scan signals. Therefore:

- fast scan data should not be analyzed with spectral methods;
- spectral analysis of burst data must allow for the excessive filtering.

The filters on the data acquisition system were upgraded for the Amauligak F-24 deployment.

## **5. OVERVIEW OF MOLIKPAQ EXPERIENCE**

### **5.1 Tarsiut P-45**

#### **5.1.1 Deployment**

The first Molikpaq deployment was at the Tarsiut P-45 wellsite, as seen in Figure 5.1, where the structure was set down late in the summer of 1984 after it had been towed from Japan to the Canadian Beaufort Sea. This deployment site was located about 75 km offshore, in about 26 m of water. The design and construction activities related to the deployment have been described by Jefferies et al, 1985 in a paper titled "Molikpaq Deployment at Tarsiut P45", ASCE Conference Civil Engineering in the Arctic Offshore, San Francisco.

As presented in Section 2, the Molikpaq was originally designed to resist an unfactored global ice load of 620 MN. However, during the structure construction phase and before the first Beaufort Sea deployment, the results of a joint industry research program at Hans Island regarding multi-year ice forces became available. These results were based on large scale ice force measurements against a natural island (Hans Island) and suggested that thick ice failure pressures and the associated global ice loads were not as high as those assumed during the original Molikpaq design criteria work. As a result, the design ice load for the caisson's first deployment was reduced from 620 MN to 500 MN. This design load estimate was evaluated from both a deterministic and probabilistic perspective and at the time, was felt to reasonably represent a 25 year return period value. The dynamic ice loading frequency and amplitude criteria developed during the original design stage remained unchanged while the local loading criteria had already been accommodated in the caisson's structural design.

A schematic sequence of the activities involved in deploying the Molikpaq are shown on Figure 5.2. Prior to the Molikpaq's arrival and before any construction activities were initiated, a detailed site survey was completed to establish the foundation conditions at the deployment location and assess the need to excavate weak surficial sediments. The survey indicated 3.5 m of weak sea-bottom material which was subsequently removed using a trailer suction hopper dredge. The subcut was filled with dredge loads of high quality sand ( $\geq 300$  microns) hauled primarily from the Ukalerk borrow source.

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Figure 5.1: The Molikpaq at Tarsiut P-45.

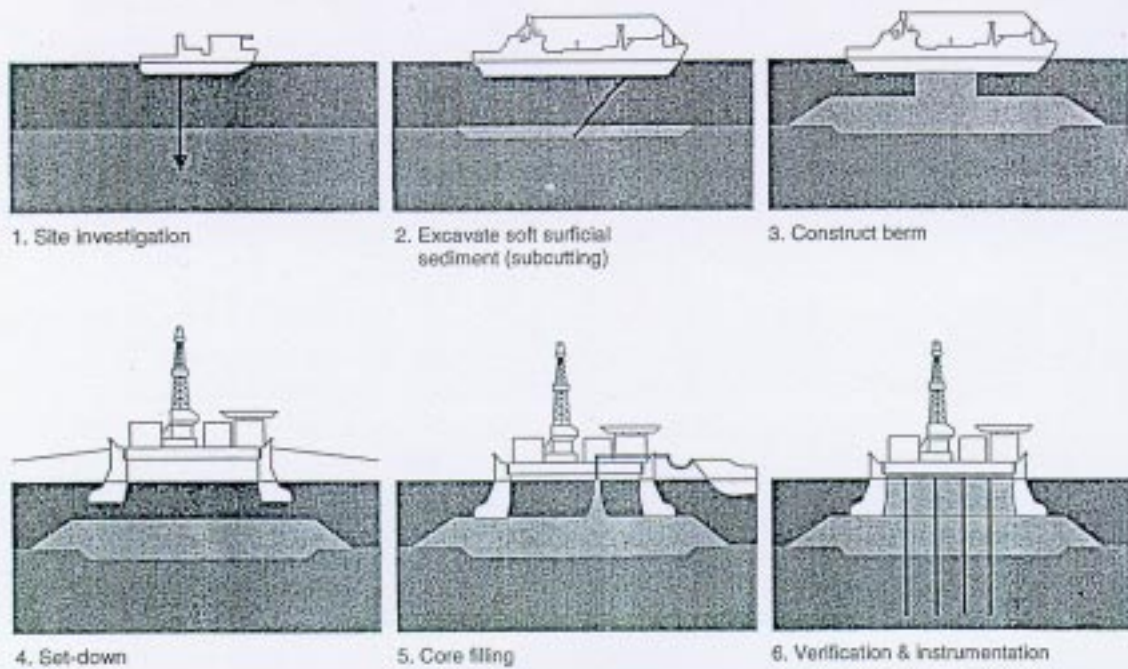


Figure 5.2: Typical deployment sequence for the Molikpaq.

Following filling of the subcut with 115 000 m<sup>3</sup> of sand, a 6 m high berm was constructed with the dredge, primarily using a bottom valve discharge method for a total in-place berm quantity of 230 000 m<sup>3</sup> of sand material. Subcut and berm construction operations began on August 9th and were completed by September 19th. During the construction period, open water and light ice concentration conditions prevailed, and few construction difficulties were experienced.

Once the berm surface was levelled and tested for adequacy in terms of its density, the Molikpaq was towed to the site location and ballasted on to the berm. The caisson's core was then filled with 115,000 m<sup>3</sup> of dredged sand to a height of 2 m above sea level. This operation was accomplished by discharging sand from the hopper dredge through a floating pipeline that was connected to the Molikpaq's built-in pipework. The sand was discharged into the Molikpaq's core through a single spigot, the core surface levelled, and the ballast tanks filled with sea water to about 20 m above the caisson base. The total sliding resistance of Molikpaq was estimated as 750 MN.

In terms of ice loads and ice/structure interaction behaviour, the key points that should be noted are highlighted as follows:

- the caisson's set down draft was 19.5 m (between the waterline and the berm's surface);
- the caisson's outer faces were near vertical at the waterline, (8 degrees from vertical). The Molikpaq's more sloped wall segments (23 degrees from vertical) started at about 3 m below the waterline;
- the berm's surface extended 15 m minimum beyond the toe of the caisson, and the berm slopes were typically 1 vertical to 7 horizontal.

### **5.1.2 Ice Conditions**

General ice conditions in the Canadian Beaufort Sea were not unusual during the winter of 1985/85. Freeze-up commenced in the late October period, with thin first year ice beginning to form in the offshore area. In the shallower waters to the south of Tarsiut P-45, the nearshore landfast ice zone developed over the mid October to late December time frame and by early January, the fast ice edge had reached its maximum extent at the 20 m isobath, about 10 km south of the deployment site.

Grounded rubble also formed on the remnant shallow caisson island berm Tarsiut N-44 located 10 km to the east of the Molikpaq. This tended to extend the fast ice locally and in turn, afforded the Molikpaq some protection from moving pack ice, which drifted predominantly from the east to the west. During freeze-up, a few areas of low to moderate second year ice concentrations were also present in the offshore region, although the main polar pack ice boundary was well to the north.

In November and December, winds moved some of these second year ice concentrations towards the Molikpaq location and a number of small to moderately sized second year floes which were frozen into the thin first year pack ice failed against the structure. One vast second year floe that was about 15 km in diameter drifted to within 1 km of the Molikpaq in late November. This floe, which contained ridges in excess of 20 m in thickness, would have put the Molikpaq to a severe test but stopped before it interacted with the structure. A SAR image of the floe is shown in Figure 5.3. In late December, storm winds from the southeast cleared all of the second year ice from the Molikpaq's operating area and no further second year ice interactions were seen. In addition, the multi-year ice stayed well to the north and at no time was a concern to the Molikpaq during the 1984/85 operating season.

For the remainder of the winter, the first year ice cover continued to grow and the Molikpaq remained in moving first year pack ice conditions. Ice thicknesses ranged from less than 0.5 m to 1.8 m and were quite variable, with frequent occurrences of thin ice that resulted from the refreezing of open water areas, created by ice dynamics. Ice drift speeds typically varied between 0.1 and 0.7 m/sec and were predominantly from east to west, although on short time scales, the ice moved against the caisson from all directions. For 20% of the time, the pack ice was stationary. Break-up and ice clearance occurred in the late May to late June period with open water conditions occurring in early July.

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Figure 5.3: In late November, a large second year ice flow about 10 km in extent (referred to as Pacman) approached the Molikpaq from the northwest, but stopped about a kilometre west of the structure, due to the constraining influence of the landfast ice zone on the moving pack. It drifted off to the west several days later and never impacted the Molikpaq. This figure shows a radar image (SAR) of the general area at this time, where the radar reflection from the second year ice is white and the first year ice appears black. The Molikpaq's location is shown as a white circle. A broken ice wake (white line) created as the ice moved past the structure can also be seen.

The ice conditions that the Molikpaq was exposed to during the 1984/85 winter season were quite typical of the Beaufort Sea's normal pack ice environment. In terms of the ice/structure interactions observed, it is very significant that a stable grounded rubble field did not form around the Molikpaq over the course of the winter, as had been the case with all other Beaufort structures deployed to that time. This was a consequence of the caisson's deep set down draft and relatively small berm, in combination with the nature of the ice action against its near vertical waterline faces. Since no protection was afforded by grounded ice rubble, the Molikpaq was the first wide Arctic structure to be directly exposed to moving ice throughout the winter period. As a result, the full scale 1984/85 observations of ice failing directly against it were the first of their kind, and represented a unique and very important source of information regarding ice loads and effects.

The range of peak failure pressures and global loads estimated for the 1984/85 winter period at Tarsiut P-45 are summarized in Table 5.1. Typical Molikpaq caisson, core, berm and foundation responses to these ice loads are shown in Table 5.2. All responses were in line with design load level predictions, which are also shown in the table.

**Table 5.1 - Typical Ranges of global ice load levels and effective ice failure pressures for first year ice at Tarsiut P-45 as a function of ice failure mode**

Ice Failure Mode	Typical Range of Peak Failure Pressures Across the Loaded Width (MPa)	Typical Range of Global Loads* (MN)
Crushing	1.0 - 1.5	50 - 150
Flexure and Buckling	0.2 - 0.6	20 - 50
Mixed Modal	0.4 - 0.8	20 - 80
Fracture	N/A	20 - 30
Ridges	N/A	30 - 100

\* Global load levels were highly dependent on the contact length over which the ice was failing against the caisson

**Table 5.2 - Summary of Instrumentation Response at Tarsiut P-45**

Type of Instrument	Location	Typical Response Ice Load 100 - 200 MN	Expected Response Ice Load 500 MN
Medof Panels	N, NE, E	200 - 500 Tonnes/panel	1000 Tonnes/panel
Strain Gauges	Ice Face	750 Microstrains	1500 Microstrains
	Bulkheads	300 Microstrains	600 Microstrains
Extensometers	Caisson-Deck	10 mm	50 mm
	Deck-Conductor	3 mm	15 mm
Accelerometers & Tiltmeters	Caisson, Core	Up to 3% g	> 10% severe loading
Total Pressure Cells	Caisson Base	±15-20 kPa (usually at leading edge)	± 80 kPa
Piezometers	Sand Core & Berm	±10 kPa	± 30 kPa
Inclinometers	Core, Berm, Foundation	< 20 mm	100 mm

### 5.1.3 Deployment Summary

A summary listing of ten days at Tarsiut P-45 that contain ice-structure interactions with good documentation that could also be used for further research have been presented in Table 5.3. These events provided the first opportunity to compare full scale ice/structure interactions with the assumptions and criteria developed during the Molikpaq's design phase. Based on a review of all available data, the key points to be noted from the Molikpaq's 1984/85 deployment at Tarsiut P-45 include:

- no multi-year ice interacted with the structure;
- some second year ice interactions occurred during the late freeze-up period;
- over the course of the winter, the Molikpaq was directly exposed to drifting first year ice and encountered level ice of various thicknesses, pressure ridges and rubble;

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Table 5.3 - Ice Loading Events Suitable for Detailed Analysis: Tarsuit P-45

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ICE LOADING EVENTS SUITABLE FOR DETAILED ANALYSIS: TARSUIT P-45

DATE & TIME	FAILURE MODE	ICE THICKNESS AND VELOCITY	EVENTS	DAILY FILE	POST FILE (114)	EVENT FILE (114)	VIDEO RECORD	COMMENTS
Nov 2084 10:40 hrs Nov 2088 11:20 hrs		27 ft with 100% ice at 100% velocity	The structure was hit by ice with a velocity of 100% and a thickness of 27 ft. The ice was broken into small pieces and the structure was damaged. The ice was broken into small pieces and the structure was damaged.	041240007 241241120		041240008 241241120		The structure was hit by ice with a velocity of 100% and a thickness of 27 ft. The ice was broken into small pieces and the structure was damaged. The ice was broken into small pieces and the structure was damaged.
Nov 2100 04:05 hrs		Aug 15.007 m/s @ 100%	The structure was hit by ice with a velocity of 15.007 m/s and a thickness of 15 ft. The ice was broken into small pieces and the structure was damaged. The ice was broken into small pieces and the structure was damaged.	Nov 21, 45, 27, 28 200000000				The structure was hit by ice with a velocity of 15.007 m/s and a thickness of 15 ft. The ice was broken into small pieces and the structure was damaged. The ice was broken into small pieces and the structure was damaged.
Nov 2100 04:05 hrs		15 m 0.01 m/s @ 140°	The structure was hit by ice with a velocity of 15 m/s and a thickness of 15 ft. The ice was broken into small pieces and the structure was damaged. The ice was broken into small pieces and the structure was damaged.	Nov 21, 45, 27, 28 200000000				The structure was hit by ice with a velocity of 15 m/s and a thickness of 15 ft. The ice was broken into small pieces and the structure was damaged. The ice was broken into small pieces and the structure was damaged.
Nov 2100 07:40 hrs		2.9 m 0.01 m/s @ 240°	The structure was hit by ice with a velocity of 2.9 m/s and a thickness of 2.9 ft. The ice was broken into small pieces and the structure was damaged. The ice was broken into small pieces and the structure was damaged.	Nov 21, 45, 27, 28 200000000				The structure was hit by ice with a velocity of 2.9 m/s and a thickness of 2.9 ft. The ice was broken into small pieces and the structure was damaged. The ice was broken into small pieces and the structure was damaged.
Nov 2100 11:00 hrs		2.8 m 0.01 m/s @ 200°	The structure was hit by ice with a velocity of 2.8 m/s and a thickness of 2.8 ft. The ice was broken into small pieces and the structure was damaged. The ice was broken into small pieces and the structure was damaged.	Nov 21, 45, 27, 28 200000000				The structure was hit by ice with a velocity of 2.8 m/s and a thickness of 2.8 ft. The ice was broken into small pieces and the structure was damaged. The ice was broken into small pieces and the structure was damaged.
Nov 2100 07:30 hrs 11:00 hrs		2.8 m 0.01 m/s @ 200°	The structure was hit by ice with a velocity of 2.8 m/s and a thickness of 2.8 ft. The ice was broken into small pieces and the structure was damaged. The ice was broken into small pieces and the structure was damaged.	Nov 21, 45, 27, 28 200000000				The structure was hit by ice with a velocity of 2.8 m/s and a thickness of 2.8 ft. The ice was broken into small pieces and the structure was damaged. The ice was broken into small pieces and the structure was damaged.

LEGEND: FAILURE MODES: FLEURE, BUBBLE PILE, PILE DRIFTING

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ICE LOADING EVENTS SUITABLE FOR DETAILED ANALYSIS - TARSUUT P-45

Table 5.3 - Ice Loading Events Suitable for Detailed Analysis: Tarsuut P-45 (continued)

DATE & TIME	FAILURE MODE	ICE PROXIMITY AND VELOCITY	SYNOPSIS	ONLY FILE	FILE NUMBER (NO)	AVAILABILITY STATUS	VIDEO RESPONSE	COMMENT
May 04/96 12:15 hrs		1.3 m 0.24 m/s at 20°	A bulging event with an impact by the ice on the bow. The ice was approximately 1.3 m thick and moving at 0.24 m/s. The impact resulted in a local buckling of the hull plating. The ice was subsequently removed by the crew.	None	16403104			The ice was in the bow. The structural response is not documented in particular the structural & global responses are not documented. Local buckling resulted in a 20% increase in resistance (1.11 MPa).
May 04/96 14:20 hrs		1.7 m 0.22 m/s at 20°	The event occurred after impact with ice on the bow. The ice was approximately 1.7 m thick and moving at 0.22 m/s. The impact resulted in a local buckling of the hull plating. The ice was subsequently removed by the crew.	None	16403105			The phenomenon was similar to the one described in the previous event. The ice was in the bow and resulted in a local buckling of the hull plating.
June 20/96 10:27 hrs		0.8 m 0.24 m/s at 20°	Large ice pile-up on the bow during an oblique impact event. The ice was approximately 0.8 m thick and moving at 0.24 m/s. The impact resulted in a local buckling of the hull plating. The ice was subsequently removed by the crew.	None	16403106			The phenomenon was similar to the one described in the previous events. The ice was in the bow and resulted in a local buckling of the hull plating.

ICE LOADING EVENTS SUITABLE FOR DETAILED ANALYSIS - TARSUUT P-45

MODES:  FAILURE  FAILURE FILE  FAILURE BRITTLING

- . the Molikpaq's near vertical faces acting in combination with its deep set down draft resulted in direct ice action against the caisson throughout the winter period, and tended to prevent the formation of a protective annulus of grounded rubble around it;
- . a variety of failure modes were observed as the ice cover moved against the Molikpaq, with the ice load levels being strongly dependent upon the manner in which the ice failed against the caisson's outer wall;
- . the highest ice loads were associated with continuous ice crushing against the Molikpaq, with some of these crushing events including periods of pulsating or cyclical ice loads that resulted in ice induced structural vibrations;
- . the ice loads that the Molikpaq experienced from the first year ice conditions encountered over the 1984/85 winter period were well within the structure's design bounds and its overall resistance capability;
- . the 1984/85 response measurements tended to confirm many of the Molikpaq's design assumptions. The measurements suggested that ice loads could be higher in thicker ice and that ice loading dynamics did occur, but both areas appeared to be acceptable in terms of the Molikpaq's design.

## **5.2 Amauligak I-65**

### **5.2.1 Deployment**

The second Molikpaq deployment was at the Amauligak I-65 location, where the caisson was set down in late September 1985, after being moved from Tarsiut P-45. The Amauligak site was located about 60 km north of Tuktoyaktuk, in 31 m of water.

Amauligak I-65 was situated about 30 km to the east of the Tarsiut P-45 well that had been drilled the year before. In terms of winter ice conditions, there was no significant difference in the expected ice conditions or the likelihood of multi-year ice encounters at the Amauligak I-65 location from those at the Tarsiut P-45 wellsite. Because the ice loads and structural responses that had been measured during the Molikpaq's first deployment had been relatively low in comparison to the 500 MN global design load level, there were some discussions about reducing the global ice design load for the second

deployment. However, the fact that the Molikpaq had not encountered multi-year ice during the 1984/85 Tarsiut deployment and had only obtained one year of operating experience in first year ice (and some second year), meant that more severe ice conditions could be experienced. As a result, the 500 MN global ice design load, representative of a 25 year return period event, was retained for the Molikpaq's Amauligak I-65 deployment. Although the Molikpaq had experienced some ice induced vibrations at Tarsiut P-45, the structure's responses were within predicted levels. As a result, the dynamic ice loading criteria for the Amauligak I-65 deployment were kept the same as the original design criteria.

A geotechnical survey was carried out at Amauligak I-65 during the summer of 1984 to assess the site specific foundation conditions. This survey indicated that the foundation at the deployment site consisted of 8 m of soft clay, overlaying 29 m of dense sand, followed by an 11 m thick unit of stiff clay. The soft surficial clay layer was too weak to support the weight of the Molikpaq and berm, and so required excavation as a subcut. The subcut was excavated in October 1984 and August 1985.

Sand placement operations, which were carried out with three trailer suction hopper dredges, began in mid August and were completed by mid September. Over the course of the summer, the presence of variable concentrations of drifting ice hampered the dredging activity. However, ice management support was provided on an as required basis by one and sometimes two of BeauDril's Arctic Class IV icebreakers as shown in Figure 5.4, and was very effective in sustaining the efficiency of the dredging operation. The 8 m subcut was infilled with 440,000 m<sup>3</sup> of sand, followed by construction of the berm with an additional 830,000 m<sup>3</sup> of sand. In total, about 1,300,000 m<sup>3</sup> of sandfill material from local borrow sources were moved and placed during a month and a half construction period. Once the berm was levelled and tested for density, the Molikpaq was towed over the location, ballasted on to the berm, and the core space was filled with about 140,000 m<sup>3</sup> of sand to a height of 1.5 m above sea level. Corefill placing and levelling operations took four days to complete. The ballast tanks were filled with sea water to about 20 m above the base, with a resulting ultimate resistance of 750 MN against horizontal sliding.

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Figure 5.4: Variable concentrations of first year ice hampered the dredging activities that were associated with the construction of the Amauligak I-65 subcut and berm. Ice management support was provided by BeauDril's Arctic Class IV icebreakers which proved very effective in allowing continued dredging activities when significant ice was present.



Figure 5.5: The Molikpaq at Amauligak I-65.

From an ice loading perspective, key aspects of the Molikpaq's Amauligak I-65 deployment configuration included:

- the caisson's outer faces were 8 degrees from vertical at the waterline;
- the caisson's set down draft was 19.5 m;
- the berm's surface extending about 15 m from the toe of the caisson with the berm's slopes at 1 vertical to 8 horizontal.

### **5.2.2 Ice Conditions**

During the 1985/86 winter season, freeze-up began in late October, with the formation of thin first year ice across the general offshore region. At the time, the edge of the polar pack was further south than normal, with some low to high concentration pockets of multi-year ice stretching southwards into the intermediate water depths, across the same latitude as the Amauligak location. In addition, there were a few areas of second year ice (remnant first year ice from the previous summer) drifting with the growing pack. Further to the south, the landfast ice formed over the October through late December period, reaching its maximum extent in early January, about 15 km south of the Molikpaq at the 20 m water depth contour.

Over the course of the freeze-up and early winter period, first year pack ice moved past the Molikpaq as shown in Figure 5.5. On several occasions, the first year ice contained small second year ice floes. During this period, there were no major offshore storms that moved the second year ice and polar pack edge further to the north, as had been the case the year before. Typical first year ice thicknesses ranged from 0.3 to 1.3 m and drift speeds varied from 0.1 to 0.6 m/sec. Predominant ice movements were from east to west, but on shorter time scales, movements from all directions occurred. In general terms, the ice conditions over the first part of the winter at Amauligak I-65 were not dissimilar to those encountered at the Tarsiut P-45 location.

However, in late February and early March, the predominant east to west drift of the Beaufort's transition zone pack ice was interrupted by strong northwesterly winds, which brought variable concentrations of second and multi-year ice southwards, into the vicinity of the Molikpaq's deployment location. Over the first week of March, a number of multi-year and second year ice floes moved across the Amauligak location, impacting the Molikpaq in the process. A STAR image and photograph of the ice conditions are shown on Figure 5.6. On March 8th, the southerly ice drift stopped, being constrained by the landfast ice to the south. Over the next month, the ice around Amauligak remained stationary and did not begin moving until April 12th, when strong offshore winds moved the pack to the northwest. As the ice moved offshore, the Molikpaq encountered several more multi-year ice interactions as illustrated in Figure 5.7, prior to entering the open waters of a floe lead, that formed between the fast ice edge and the pack. For the remainder of the winter and spring, the ice cover continued to drift, with the Molikpaq encountering first year ice which, on occasion, contained some multi-year ice floes. Break-up commenced in the mid May time frame with the gradual loosening of the winter pack ice. Over the late May and June period, large floes continued to move against the Molikpaq but by early July most of the winter ice had cleared and the Molikpaq was located in open water.

The ice conditions that the Molikpaq was exposed to during the 1985/86 winter season were more severe than those encountered in its first deployment at Tarsiut P-45. However, the increased severity of the ice conditions experienced at Amauligak I-65 was directly related to the occurrence of multi-year ice in mid winter, rather than the nature of the first year ice cover itself. From a first year ice perspective, the regional ice cover was slightly thicker than in 1984/85, but was still representative of normal winter conditions in the Beaufort Sea's pack ice environment. The multi-year ice intrusion gave rise to thicker ice interactions and led to the increased winter severity "ranking". The multi-year ice interaction information is particularly unique because no other offshore structure has encountered these types of ice conditions to date.

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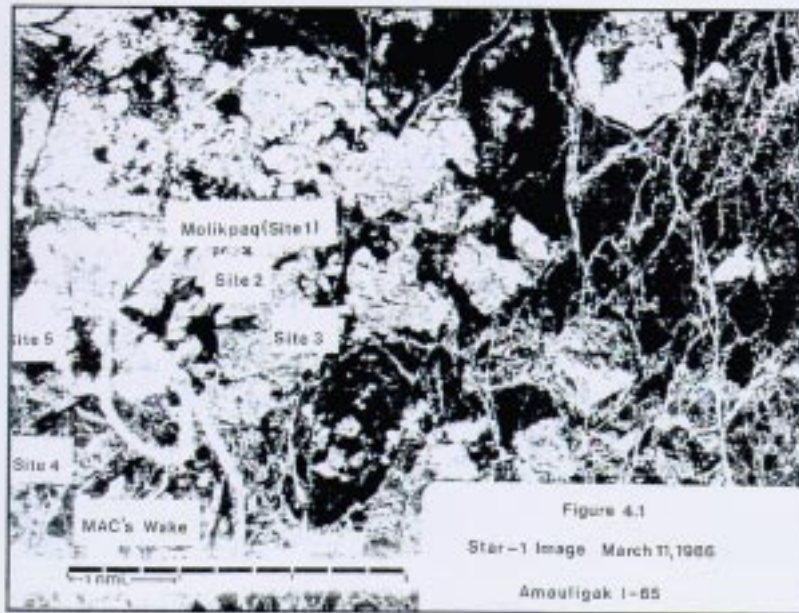


Figure 5.6: The upper figure shows a large multi-year ice flow moving against the Molikpaq on March 8th, 1986. The lower figure is a radar image of the general ice conditions around the Molikpaq in mid March with old ice floes indicated as white radar reflections and first year ice typified by black returns. The Molikpaq's wake that was created as the result of ice moving past it is evident in both figures.

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Figure 5.7: The upper photo shows multi-year ice crushing against the Molikpaq on April 12th where the ice extrusions caused by ice clearance can be seen, while the lower photo shows representative ice extrusion debris that has been turned back by the ice deflector.

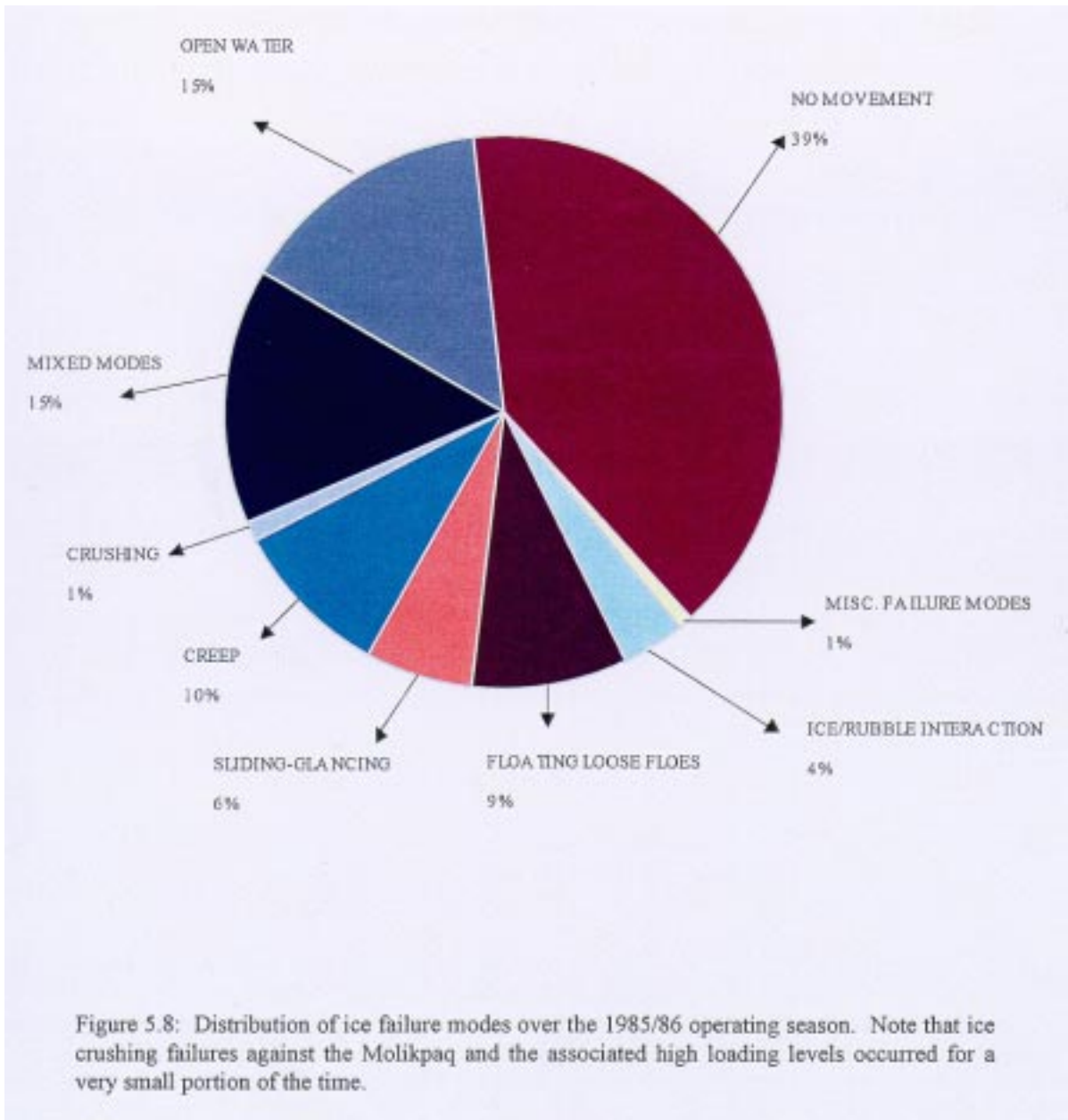
As was the case in 1984/85, a stable grounded rubble field did not form around the Molikpaq at the Amauligak I-65 deployment location. Again, this is a significant observation and was a consequence of the Molikpaq's deep set down draft (19.5 m) and relatively small berm crest, in combination with the nature of the ice action against its near vertical waterline faces. Since no protection was afforded by grounded ice rubble, the caisson was directly exposed to moving ice throughout the winter period.

As noted earlier, the ice failure mechanisms associated with various Molikpaq ice interactions are important since they determine the magnitude and distribution of ice pressure that the ice cover can exert and, in turn, govern the ice loads and Molikpaq responses that result. The frequency of occurrence of various failure modes over the 1985/86 winter period is shown in Figure 5.8 as based upon a review of more than 6000 hours of Molikpaq ice interaction video recordings that were obtained over the nine month winter period. Here, the cumulative times characterized by stationary ice and open water are included to provide a more complete perspective of the range of winter ice conditions encountered.

The key points related to the ice failure modes observed over the nine month monitoring period in the winter of 1985/86 are as follows:

- open water conditions or no ice movement occurred for 54.9% of the time;
- creep (slow ice movement) occurred 9.5% of the time;
- sliding of ice floes around the structure, and ice interactions at the outer edge of floating rubble adjacent to the structure occurred 19.5% of the time;
- mixed modal failures comprised of bending and crushing occurred 15% of the time;
- crushing occurred only 1.1% of the time, of which 90% and 10% involved first year ice and multi-year ice, respectively.

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As was the case at Tarsiut P-45, the global ice loads and failure pressures measured at Amaulikak I-65 were strongly dependent on the manner in which the ice failed against the Molikpaq. First year ice loads were generally less than 100 MN and were highest during ice crushing events. The peak global ice loads occurred in the March, April and May and were associated with multi-year ice interaction events. Table 5.4 provides a summary of the highest ice loads, which again were caused by simultaneous ice crushing and ranged from 230 MN to about 500 MN. The reader is referenced to a paper by Jefferies and Wright, 1988 titled "Dynamic Response of Molikpaq to Ice Structure Interaction", OMAE, Houston, Texas, for further details concerning these high load events.

Deformation monitoring in inclinometers located in the core indicated that these events caused some permanent horizontal sand displacement. Table 5.5 summarizes the lateral deformations measured in the seven inclinometer casings. All displacements shown in the table occurred at the interface of the bottom of the core and the berm and within the core itself. Only nominal movement occurred at the subcut/seabed interface and in the berm. No measurable permanent deformation occurred as a result of ice events of less than 150 MN.

**Table 5.4 - Peak Global Load Events**

Date/Time	Description	Ice Drift Speed	Peak Ice Load (MW)	Failure Mode (s)	Normalized <sup>(c)</sup> Dynamic Amplitude
Mar 7 15:30-17:43	Full penetration of a 200 x 300 m multi-year floe	0-0.06 m/s	230	Crushing at North, NW, West Faces	16%
Mar 8 17:32-18:37	75 m of slow penetration into a 1000 m x 2000 m multi-year floe	0.02 m/s	320	Crushing at North, NW, West Faces. Some floe fracture.	26%
Apr 12 08:00-08:45	Interaction with ice hummock in 3-5 m level ice	0.06 m/s	>500	Crushing followed by break out at ridge	45%
May 12 03:01- 03:26	4 nmi x 8 nmi of thick first year ice with ___ yr inclusion	0.2 slowing to 0 m/s	250	Crushing at North Face	20 to 45%

**Table 5.5 - Slope Inclinometer Lateral Displacement - Event Summary**

Lateral Displacement (mm)									
Event Date 1986	Load Estimate Tonnes	Direction To:	North	NE	West	Centre	East	South	SW
Mar 7/8	30,000	East, SE, South	12 S	16 SE	8 N	*	20 E	*	12 NW
Apr 12	50,000	West, NW	18 NW	28 N	24 N	12 W	**	30 SW	16 W
May 12	25,000	South	14 S	14 S	0	0	0	0	0

\* casing not profiled for this event

\*\* casing sheared in core during event.

The peak load for the season occurred on April 12, 1986, during crushing of a multi-year ice floe about 4 m thick that contained a 12 m thick hummock. The peak responses for the accelerometer, piezometer and extensometer sensors are shown in Figure 5.9. A comparison with the 1985 predictions of Molikpaq response to a 500 MN load (Table 5.2) shows that the piezometers response on April 12 was higher than anticipated. Part of the core sand adjacent to the loaded east face of the caisson liquefied, causing a reduction in the resistance capability of the Molikpaq. However the cyclic loading that caused the increase in pore water pressure in the core sandfill reduced as the hummock advanced into the caisson, and pore water pressures started decreasing immediately after the ice sheet experienced a flexural fracture behind the hummock. At this time the liquefied sand was limited to a zone adjacent to the loaded face and above the base of the Molikpaq. Deflections of the caisson face at deck level during the crushing of level ice prior to the hummock were measured at approximately 80 mm during this crushing event. As shown in Table 5.5 the permanent deformation at the base of the sand core as measured in the centre inclinometer after the event was 12 mm.

Concern has been raised that the loads reported for the April 12, 1986 liquefaction event are too high, and that liquefied soil could not have supported the load. In particular it has been asserted that the load on that date should be limited to the available resistance from caisson dead weight only.

Two comments are particularly noteworthy when considering the April 12, 1986 event. These are that:

- . only 2 of the 18 piezometers in the sand core showed liquefaction. Of the remaining 16 gauges, the majority show small to negligible pore water pressure increase. This confirms that liquefaction was localized;
- . if the measured pore water pressures shown in Figure 5.9 are used to calculate an available resistance which includes the liquefied zone, the available global resistance of the Molikpaq is still in excess of 500 MN.

Finally, it should be appreciated that overall the Molikpaq ice load events form a consistent pattern of deformation versus load as shown in Figure 5.10. In fact, the April 12, 1986, event can be eliminated from the dataset without changing the trend of ice load versus extensometer monitored caisson deformation.

### 5.2.3 Deployment Summary

The following bullet points provide a summary of the observations made about ice loading at the Amauligak I-65 location.

- . Over the course of the winter, the Molikpaq was exposed to a wide range of drifting first year ice, including a variety of ice thicknesses and pressure ridges. Some second year ice interactions also occurred during the freeze-up/early winter period.
- . The structure experienced a number of multi-year ice interactions in mid winter. The multi-year ice was representative of extreme winter ice conditions but the floes that impacted the Molikpaq were not particularly severe.
- . The Molikpaq became the first offshore structure to experience direct interactions with thick multi-year ice floes and was severely tested, both in terms of peak global ice loads and the associated ice induced vibrations.
- . As was the case in 1984/85, the Molikpaq's near vertical faces acting in combination with its deep set down draft resulted in direct ice action against the caisson throughout the winter period, and prevented the formation of a protective annulus of grounded rubble around it.



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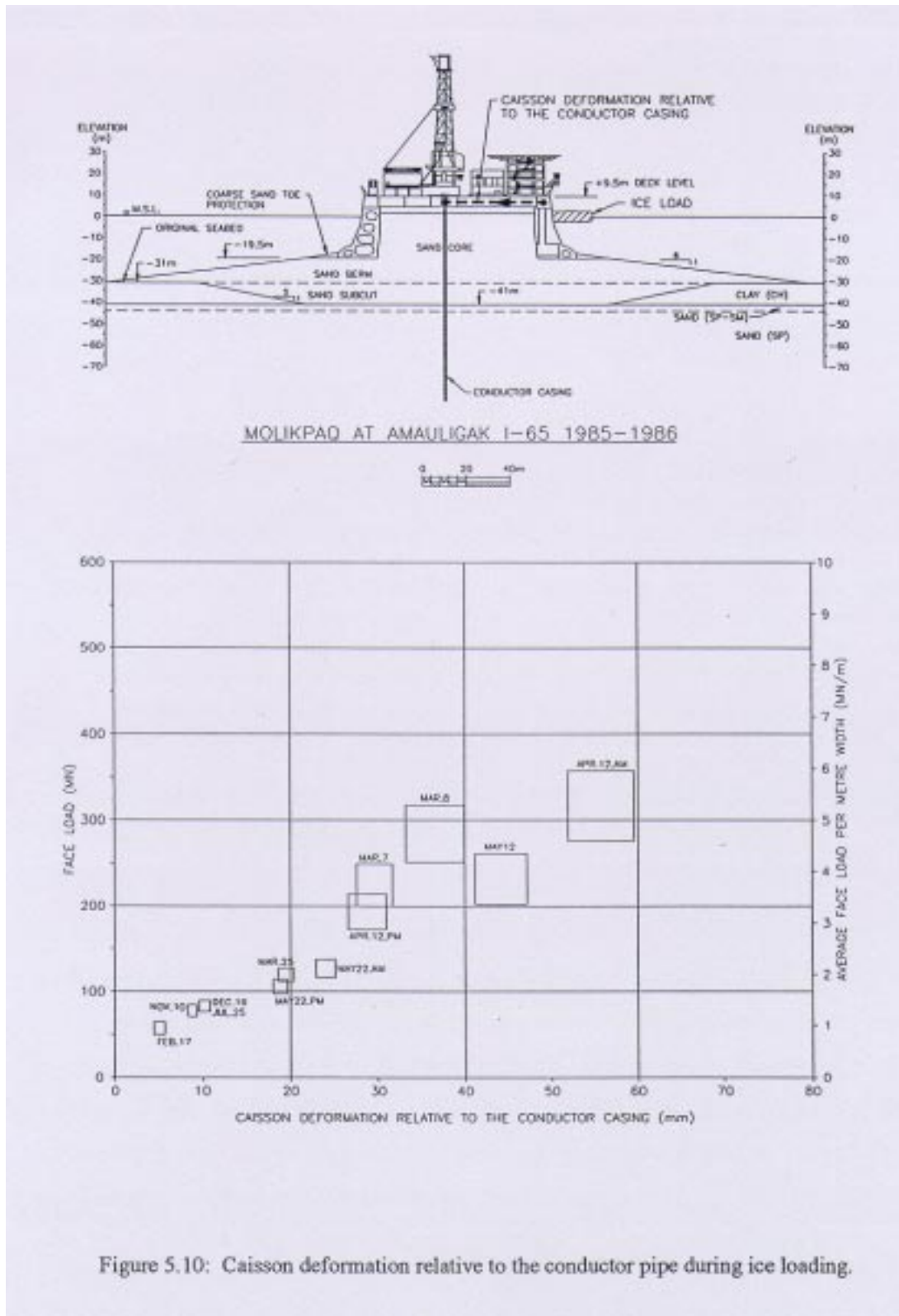


Figure 5.10: Caisson deformation relative to the conductor pipe during ice loading.

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- . A variety of failure modes were again observed as both first and multi-year ice moved against the Molikpaq, with the ice load levels being strongly dependent upon the manner in which the ice failed against the caisson's outer wall.
- . The ice loads that the Molikpaq experienced from the first year ice conditions encountered over the 1985/86 winter period were similar to 1984/85 and well within the structure's design bounds and its overall resistance capability.
- . The multi-year ice loads were substantial higher because of the increased ice thicknesses involved, although the ice failure pressures were similar to those measured in first year ice.
- . The highest ice loads were associated with continuous crushing of multi-year ice against the Molikpaq, with some of these crushing events including periods of pulsating or cyclical ice loads applied simultaneously across its loaded face, that resulted in significant ice induced structural vibrations.
- . The Molikpaq's responses (caisson, core, berm and foundation) were all within acceptable tolerances in first year, but the structure's sand core was fatigued in one of the multi-year ice interaction events, confirming the importance of ice loading dynamics on the structure's overall response and resistance capability.
- . The 1985/86 measurements established the importance of thick multi-year ice floe interactions and the associated occurrence of large global loads and relatively high frequency cyclic loading, both being key for the structure's future deployment designs.

The Amaulikak I-65 provides a unique data set of ice structure interactions. Key ice loading events have been identified from nineteen days during the winter season which represent periods with both good ice documentation and response data. Typically each key loading event includes a brief description of the ice interaction sequence, contains the data acquisition system data files, the ice condition and ice interaction records, and the available photographic and video records. These events are summarized in Table 5.6, and form the basis for the information collated and later stored on CD-ROM. Further information on the ice event database is provided in Appendix I.





Table 5.6 - Ice Loading Events Suitable for Detailed Analysis: Amauligak I-65 (continued)

DATE & TIME	FAILURE MODE	SPEED/DIRECTION AND VELOCITY	SYMPTOMS	EVENT DATA				COMMENTS
				ENCL FILE	FILE NAME (IN ICD)	VIDEO RECORD	VIDEO FILE (IN ICD)	
March 20/96 08:42		2.7 m/s 174 m/s @ 18°	After 7 months of operation, the hull was found to be cracked along the starboard side. The crack was approximately 100 m long and 10 mm wide. The crack was located in the hull plating between the 101 and 102 frames. The crack was caused by ice loading on the starboard side of the hull.	100000114	100000001	100000001	100000001	The video attached to the report shows the crack in the hull plating between the 101 and 102 frames. The crack was approximately 100 m long and 10 mm wide. The crack was caused by ice loading on the starboard side of the hull.
April 19/96 08:42		2.7 m/s 174 m/s @ 18°	After 7 months of operation, the hull was found to be cracked along the starboard side. The crack was approximately 100 m long and 10 mm wide. The crack was located in the hull plating between the 101 and 102 frames. The crack was caused by ice loading on the starboard side of the hull.	100011412	100011412	100011412	100011412	The video attached to the report shows the crack in the hull plating between the 101 and 102 frames. The crack was approximately 100 m long and 10 mm wide. The crack was caused by ice loading on the starboard side of the hull.
April 20/96 11:05-5 13:00hrs		2.7 m/s 174 m/s @ 18°	After 7 months of operation, the hull was found to be cracked along the starboard side. The crack was approximately 100 m long and 10 mm wide. The crack was located in the hull plating between the 101 and 102 frames. The crack was caused by ice loading on the starboard side of the hull.	100011412	100011412	100011412	100011412	The video attached to the report shows the crack in the hull plating between the 101 and 102 frames. The crack was approximately 100 m long and 10 mm wide. The crack was caused by ice loading on the starboard side of the hull.
May 10/96 02:02 hrs		2.7 m/s 174 m/s @ 18°	After 7 months of operation, the hull was found to be cracked along the starboard side. The crack was approximately 100 m long and 10 mm wide. The crack was located in the hull plating between the 101 and 102 frames. The crack was caused by ice loading on the starboard side of the hull.	100011412	100011412	100011412	100011412	The video attached to the report shows the crack in the hull plating between the 101 and 102 frames. The crack was approximately 100 m long and 10 mm wide. The crack was caused by ice loading on the starboard side of the hull.
May 20/96 08:30		2.7 m/s 174 m/s @ 18°	After 7 months of operation, the hull was found to be cracked along the starboard side. The crack was approximately 100 m long and 10 mm wide. The crack was located in the hull plating between the 101 and 102 frames. The crack was caused by ice loading on the starboard side of the hull.	100011412	100011412	100011412	100011412	The video attached to the report shows the crack in the hull plating between the 101 and 102 frames. The crack was approximately 100 m long and 10 mm wide. The crack was caused by ice loading on the starboard side of the hull.
May 20/96 14:07 hrs		2.7 m/s 174 m/s @ 18°	After 7 months of operation, the hull was found to be cracked along the starboard side. The crack was approximately 100 m long and 10 mm wide. The crack was located in the hull plating between the 101 and 102 frames. The crack was caused by ice loading on the starboard side of the hull.	100011412	100011412	100011412	100011412	The video attached to the report shows the crack in the hull plating between the 101 and 102 frames. The crack was approximately 100 m long and 10 mm wide. The crack was caused by ice loading on the starboard side of the hull.
June 19/96 03:02 hrs		2.7 m/s 174 m/s @ 18°	After 7 months of operation, the hull was found to be cracked along the starboard side. The crack was approximately 100 m long and 10 mm wide. The crack was located in the hull plating between the 101 and 102 frames. The crack was caused by ice loading on the starboard side of the hull.	100011412	100011412	100011412	100011412	The video attached to the report shows the crack in the hull plating between the 101 and 102 frames. The crack was approximately 100 m long and 10 mm wide. The crack was caused by ice loading on the starboard side of the hull.
June 20/96 08:00 hrs		2.7 m/s 174 m/s @ 18°	After 7 months of operation, the hull was found to be cracked along the starboard side. The crack was approximately 100 m long and 10 mm wide. The crack was located in the hull plating between the 101 and 102 frames. The crack was caused by ice loading on the starboard side of the hull.	100011412	100011412	100011412	100011412	The video attached to the report shows the crack in the hull plating between the 101 and 102 frames. The crack was approximately 100 m long and 10 mm wide. The crack was caused by ice loading on the starboard side of the hull.

## **5.3 Amauligak F-24**

### **5.3.1 Deployment**

The third Molikpaq deployment was at the Amauligak F-24 location in 32 m of water, where the caisson was set down in September 1987. This 1987/88 deployment site was within 8 kilometres of the Amauligak I-65 location. Over the previous 1986/87 winter season, the Molikpaq had not been required for any offshore drilling work and so had been "cold stored" at Summers Harbour in the eastern Beaufort Sea.

For the Molikpaq's first two deployment locations, the Molikpaq platform had been designed to resist an unfactored global ice load of 500 MN. As noted earlier, these design ice loads had been considered as representative of 25 year return period loading events in the Beaufort Sea's first and multi-year pack ice conditions. However, on the basis of the global loads and ice induced dynamics that were experienced during the multi-year ice events in 1986, the design ice loads were increased for the Molikpaq's Amauligak F-24 deployment. The global design load that was used was 800 MN, and the dynamic ice loading criteria was defined as an extended cyclic ice load at 1 Hz (hundreds of cycles) ranging between 800 MN and 400 MN.

The site survey that was carried out prior to the Molikpaq's deployment at Amauligak F-24 indicated that the soft surficial soils required the excavation of a 12 m subcut, the deepest of any of the Molikpaq deployments. The subcut was excavated in 1985 and 1986. The main construction season for the Amauligak F-24 berm commenced in July 1987 with profiling of the subcut, infilling with sand, and then construction of the Molikpaq's submerged berm to a height of 16 m above the seafloor. A total of 2,000,000 m<sup>3</sup> of mainly sandfill material was placed in the berm and subcut, at an average daily production of about 38,000 m<sup>3</sup> per day, using a single trailer-suction hopper dredge.

Once the berm was completed and levelled, the Molikpaq was set down and the caisson's core filled with sand from the old Amauligak I-65 berm. Gravel erosion protection material was then placed around the toe of the caisson. To meet the Molikpaq's deployment design requirements in terms of its overall resistance and its resistance to cyclic ice loading, the core was then densified using explosive densification techniques.

From an ice loading and ice/structure interaction perspective, the key points to note are highlighted as follows:

- the caisson's outer faces were sloped at 23 degrees from vertical at the waterline;
- the caisson's set down draft was 16 m, with only 14 m from waterline to the top of the erosion protection material.

### 5.3.2 Ice Conditions

The ice conditions experienced over the 1987/88 winter season were less severe than in 1985/86 and, in general terms, were comparable to the 1984/85 winter season. Freeze-up at Amauligak F-24 began in late October with the formation of thin first year ice. At the time, low to moderate concentrations of second year ice were located about 30 km north of the location with the main polar pack edge lying about 100 km to the north of the Molikpaq. Over the course of the winter, the second and multi-year ice steadily receded, until the polar pack edge was located more than 200 km north of Amauligak by the following July. During freeze-up and early winter, the first year ice continued to grow, reaching a thickness of about 1 m by early January. Over this period, the landfast ice zone also developed in the Beaufort's nearshore waters, with its outer edge stabilizing about 10 km to the south of the Molikpaq. Throughout January and early February, offshore winds and the refreezing of associated lead formations, led to a decline in the general pack ice thickness to about 0.5 m. In mid February, thicker first year ice moved into the area from the east and persisted for the remainder of the winter, growing to about 1.7 m by late April.

In terms of its movement, the first year ice cover drifted throughout most of the freeze-up and early winter period. Again, ice movements were predominantly from the east to the west but on shorter time scales, were variable in terms of both speed and direction. However in early March a two month period of near stationary ice was experienced at the site. The moving pack ice bridged between the Molikpaq and the landfast ice edge, which created a landfast ice extension out to the Amauligak site. This "quasi landfast ice area" remained relatively stationary until late April and precluded any significant ice movements across the Amauligak location in March and April. Over this period, the area immediately to the north of the fast ice extension at Amauligak was covered by thin ice, with no

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substantial southerly drifts being experienced. During mid to late April, a major northerly ice movement across the general region opened a large lead off the fast ice edge, which remained in place until the ice cover cleared during break-up. At the end of the month, strong easterly winds generated waves in the lead, which broke up the stationary ice cover in the general vicinity of the Amauligak location.

Break-up was earlier than normal, occurring over the May and early June time frame. Over this period, some low concentration areas of small first year floes moved past the Molikpaq but no continuous pack ice was experienced after the late April lead formation. In addition, the Molikpaq did not encounter any large landfast ice areas drifting north, during the general break-up of the fast ice zone in June.

The ice conditions that the Molikpaq was exposed to during the 1987/88 period were typical of the Beaufort's normal pack ice environment, with the exception of the quasi-landfast ice conditions that occurred in March and April. Over the initial part of the 1987/88 winter period, the Molikpaq was directly exposed to thin moving first year ice, as it had been in its previous two deployments. However, the ice loads and interaction effects that were observed during this period were quite different from those seen at Tarsiut P-45 and Amauligak I-65. The most significant difference was associated with the formation of a grounded rubble field around the structure, which modified the nature of the overall ice/structure interaction, and in turn, had a major influence on the loads experienced by the Molikpaq and its response behaviour. This protective rubble field formed in the late December/January time frame and remained stable over the course of the winter. The fact that it formed is a very important observation.

At Amauligak F-24, the Molikpaq had been set down at a draft of 16 m, with an additional 2 m of erosion protection material around its toe. Not only did this result in a shallower caisson structure (relative to the berm) than in the previous deployments, but it also exposed a more sloped (23 degrees from vertical) caisson face to drifting ice. This deployment configuration led to the accumulation of grounded ice rubble since it induced bending ice failures and impeded ice clearance around the Molikpaq. The rubble annulus, which is shown in Figure 5.11, was very effective in providing protection and reducing the global, local and dynamic ice loads experienced by the Molikpaq. Since

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the grounded rubble formation played such an important role in the Molikpaq's 1987/88 deployment, it is discussed in more detail below.

The first evidence of rubble build-up was seen in late November. During a short high speed movement event with drift speeds approaching 1 m/sec, first year ice in the 30 cm to 50 cm range moved against the Molikpaq's east face. Over tens of minutes, a rubble pile formed that was 5 to 7 m high and extended about 20 m out from the caisson's east wall. This rubble remained grounded for several days, before ice action perpendicular to it moved it away. In mid December, another grounded rubble formation developed off the north end of the Molikpaq's east face, which extended 25 to 30 m out from the caisson. Again, mean ice thicknesses varied from 30 to 50 cm, although the drift speeds associated with this rubble formation event were somewhat slower, averaging about 40 cm/sec. Within a week, grounded rubble covered the complete east face and had grown to about 70 m in width. Sail heights in the rubble were estimated to be between 10 and 15 m, and the formation appeared solidly grounded on the Molikpaq's berm. In late December, more rubble formed off the caisson's west wall, but subsequently broke up and drifted off. This was caused by ice movements perpendicular to it, which occurred at the end of the month. At this time, the rubble on the Molikpaq's east side was sufficiently well grounded to withstand the same type of ice action against it, and remained stable.

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Figure 5.11: The Melikpaq at Amsuigak F-24, spring 1988.

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Figure 5.12 shows a plan view of the Molikpaq rubble field. The rubble was formed in a series of discrete rubble building events, with the effective cross section of the Molikpaq and rubble hybrid increasing with each event. As this cross section increased, drifting pack ice was obstructed over progressively larger widths, which led to a higher likelihood of more rubble generation, because of reduced clearance. In terms of maximum extent, the rubble field grew to about 200 x 300 m in size, including the central area of Molikpaq itself. During the initial build up of rubble adjacent to the caisson, there were no incidents that posed any threat in terms of ice overtopping.

In March and April, the general ice cover around the Amauligak location was quasi-landfast and remained stationary. Because of this, additional growth of the rubble field was restricted by the absence of ice movement, and the rubble did not grow any more. Had normal pack ice movements continued over the mid to late winter period, there is little question that more rubble building events would have occurred, which would have extended the overall size of the rubble field around the Molikpaq.

The rubble field remained in place until late April when a lead opened around the Amauligak location, exposing the grounded rubble to open water and small waves. At this time, small sections along the rubble's southern boundary were eroded and moved off. For the next month, the rubble was exposed to a combination of open water and low concentrations of drifting first year floes. Although small waves were experienced over this period, significant deterioration of the rubble field did not start until late May. Most of the rubble fragmented and moved off in the next two weeks, primarily under wave action.

### 5.3.3 Deployment Summary

Over the course of the Molikpaq's 1987/88 deployment at Amauligak F-24, maximum ice load levels were no more than 80 MN as shown in Figure 5.13. This is only 10% of the 800 MN global design load that was used for the Amauligak F-24 deployment design. Because of this, the Molikpaq's overall performance behaviour was excellent and the range of measured responses were very low. Geotechnical monitoring indicated that no significant loads or deformations occurred in the Molikpaq's core, its berm, or its foundation. Measurements from instrumentation on the caisson itself showed that no significant structural responses occurred, either static or dynamic.

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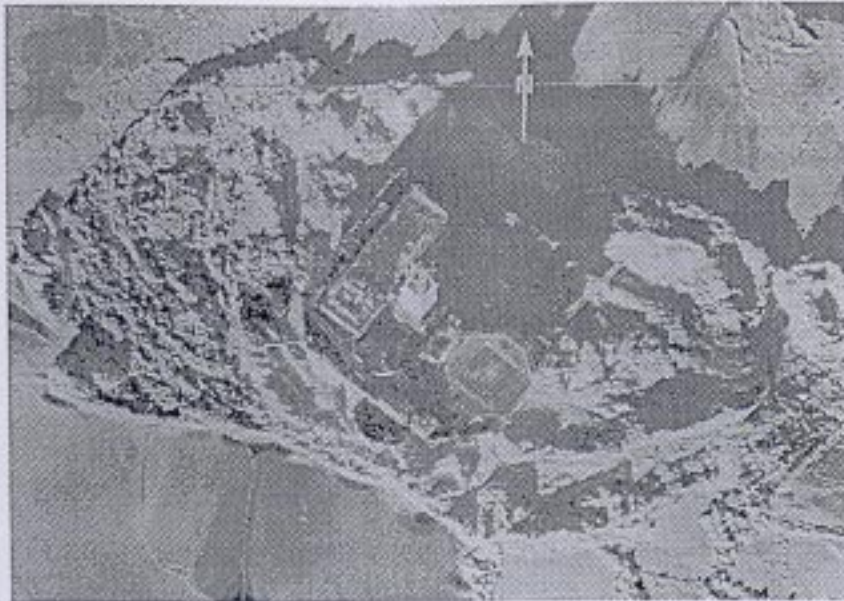


Figure 5.12: This figure shows an aerial photograph of the grounded rubble field that formed around the Molikpaq at the 1987/88 Amauligak F-24 drilling location. The rubble formation was roughly 200m x 300m in extent and was solidly grounded on the submerged berm.

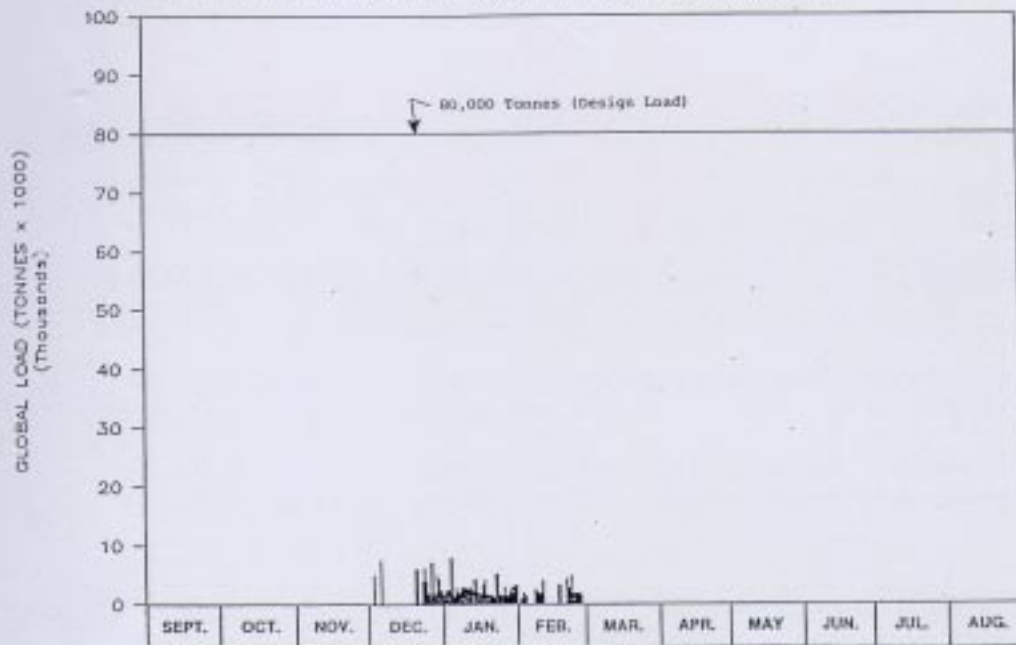


Figure 5.13: Peak daily global ice loads that were measured on the Molikpaq during the 1987/88 operating season. The ice loads imposed at the boundary of the grounded rubble formation were (in all likelihood) higher than the values shown, but were not transmitted through to the caisson itself. Obviously, the ice loads acting at the outer edge of the rubble were transmitted to the foundation through grounded portions of the rubble field and were adequately resisted.

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Overall caisson deformations and strain levels were extremely small while no accelerations were recorded from ice induced dynamics. The structural integrity of the Molikpaq was not tested at any time.

From the perspective of ice loads on the Molikpaq, the key points from the 1987/88 deployment at the Amauligak F-24 location include:

- . During the 1987/88 winter period, the structure only encountered first year ice, with no second or multi-year ice interactions. Until early March, the Amauligak location was in a pack ice environment, with first year ice of various thicknesses (including ridges and rubble fields) drifting past it;
- . The Molikpaq's shallower set down draft resulted in sloped rather than near vertical walls at the waterline (23 degrees from vertical), which caused the ice to fail in bending at relatively low load levels.
- . The sloped structure eliminated the higher ice load levels associated with the crushing failure mode that were experienced in the caisson's first two deployments, along with the associated ice induced vibrations.
- . The Molikpaq's sloped faces acting in combination with its shallower set down draft resulted in the formation of a grounded rubble field around the caisson which protected it from direct ice action over most of the winter period.
- . In March and April, the ice around Amauligak became quasi landfast, with near stationary ice conditions being experienced over this two month period;
- . Early opening of the floe lead led to easy ice conditions (low concentrations of small first year floes) for the remainder of the winter and break-up period.

## **5.4 Isserk I-15**

### **5.4.1 Deployment**

The fourth Molikpaq deployment was at the Isserk I-15 location, where the caisson was set down in late September 1989. This deployment site was much closer to shore and considerably shallower than the caisson's previous deployment locations, lying in 11.8 m of water.

The ice conditions that are commonly found around the Isserk location are characteristically different from those in the Beaufort's moving pack ice zone, where the Molikpaq had been deployed before. In the shallow nearshore waters, a relatively stable landfast ice cover normally forms by mid November, remaining in place over the winter period, and persisting well into spring break-up. This landfast ice zone, which extends seaward to the 20 m water depth contour, provides a measure of shelter in the Beaufort's nearshore waters. For example, significant ice movements are only expected during the freeze-up period, when the ice is thin. The risk of encountering the types of thicker ice features that are found further offshore is low and once the fast ice forms, is virtually eliminated. For structures located in these shallow water areas, the main considerations are related to limited displacements of thick first year ice (up to 2 m), and the probable effect of grounded rubble.

The ice/structure interaction scenarios that were considered for the Molikpaq's Isserk deployment were relatively simple, and included limited movements of thick first year landfast ice directly against the caisson, and against a range of grounded rubble field geometries. The global design load that was selected for the deployment design was 200 MN. Significant ice loading dynamics were not expected.

The Isserk site survey showed that a thin layer of weak surficial sediments was present at the deployment location, underlain by stronger foundation conditions. Prior to the Molikpaq's set down, a shallow subcut was dredged to a depth of about 2 m, over an area that was slightly larger than the caisson's footprint. About a metre of soft material was also stripped from the natural seabed around this central subcut, over an additional 75 m distance to enhance the sliding resistance of grounded rubble that was expected to form around Molikpaq. Since the water depth to the base of the subcut was only 13.5 m, there was no need for a berm, and the Molikpaq was set down directly on the prepared seafloor. To achieve the desired sliding resistance, the caisson's central core was filled with 10 m of dredged sand. With this partial sand core in place, the Molikpaq's ultimate sliding resistance was about

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300 MN. The dredging operation was carried out in late August. The caisson was towed from its "storage" location in Herschel Basin and set down in late September. Construction activities were completed within a ten day period.

From an ice loading and ice/structure interaction perspective, the key points to note related to the Isserk I-15 deployment are:

- as at the Amauligak F-24 location, the caisson's outer faces were sloped at 23 degrees from vertical at the waterline;
- the caisson's set down draft of 13.8 m was considerably shallower than any of the previous three deployments;
- no berm was required at the site; and
- the Molikpaq's core was only partially filled with sand.

#### **5.4.2 Ice Conditions**

General ice conditions in the nearshore and offshore waters of the Beaufort Sea were normal during the 1989/90 winter season. After set down, the Molikpaq remained in open water until early October, when freeze-up was first evidenced. At the time, thin first year ice began forming in the nearshore waters, with ice concentrations and thicknesses increasing throughout October, as freeze-up progressed. Drifting ice was experienced during October and early November in the general vicinity of Isserk, prior to the formation of landfast ice. Over this period, the landfast ice zone was growing seaward in a series of discrete steps, as shown in Figure 5.14. Unstable landfast ice reached the Molikpaq at the end of October but was moved off under the influence of strong offshore winds. Based upon the nature of the landfast ice edge progression and associated wind records, stable landfast ice conditions were first experienced at the Isserk location on November 5th. For the remainder of the winter, the Molikpaq was surrounded by landfast ice, as shown in Figure 5.15.

Prior to the occurrence of landfast ice at Isserk, only thin drifting ice was seen, with typical thicknesses of 20-30 cm and maximum thicknesses of 50 cm. Once the landfast ice had formed, the ice cover

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continued to grow, reaching 1.2 m in January and 1.8 m by late April. Sporadic landfast ice movements that occurred over the winter were in the order of metres to tens of metres. Potentially hazardous ice that was present in the general region remained well to the north of the Molikpaq, with the landfast ice zone preventing southward movements of these ice features. Break-up began in the late June period, with general ice clearance in early July.

Over the 1989/90 winter season, the ice conditions that the Molikpaq was exposed to were typical of the Beaufort Sea's landfast ice zone. In a relative sense, these conditions were considerably milder than the offshore pack ice encountered at the caisson's previous deployment locations. The Molikpaq's deployment configuration involved a fairly shallow set down draft and sloped caisson walls at the waterline. As expected, the combined influence of these factors led to the formation of grounded rubble around parts of the caisson, which provided some protection from direct ice action over the course of the winter. In addition, the landfast ice environment limited ice movements and consequently, the ice action experienced by the Molikpaq. Although the Molikpaq's Isserk I-15 deployment was comparatively uninteresting, relevant observations are briefly summarized as follows.

The extent and directionality of the rubble field at Isserk was different from the rubble that had formed around the Molikpaq at the Amauligak F-24 location. It was also different to most of the rubble fields that had been observed around artificial islands and shallow caisson structures in the landfast ice zone. Typically, these other rubble fields had surrounded the central structure, reflecting rubble building from different directions, caused by variations in ice movement. Many of the prior rubble fields had also shown a preferred directionality towards the northwest quadrant. In the 1989/90 Isserk case, grounded rubble fields that had formed on remnant island berms to the north of the Molikpaq tended to break the thin ice cover into smaller floes during north to south drift periods in October. This limited the continuity of the ice cover moving from the northerly quadrants and prevented rubble formation on this side of the caisson.

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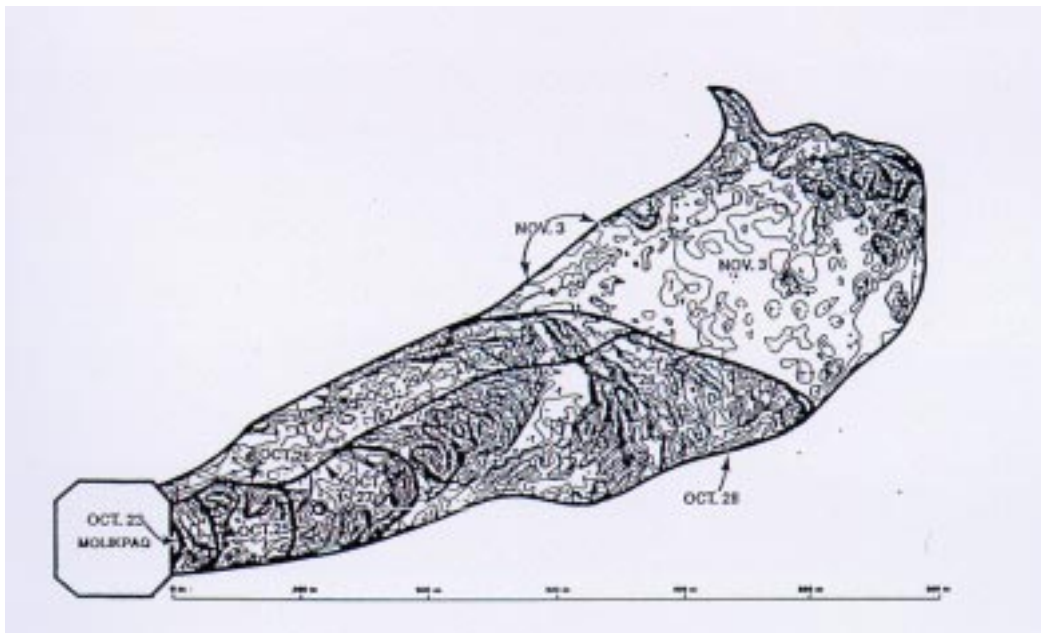


Figure 5.14: The rubble build-up sequence around the Molikpaq at the Isserk I-15 location.



Figure 5.15: Molikpaq deployed at Isserk I-15, 1989-90.

During the freeze-up period, thin mobile ice failed in bending against the Molikpaq's sloped face at low load levels, as had been the case at the Amauligak F-24 deployment. Thicker rafted ice areas that moved past the Molikpaq at this time failed in a similar manner. No crushing was observed. Direct ice action on the sides of the caisson that were not protected by the rubble resulted in bending ice failures, as shown in Figure 5.16. However, since only small, slow landfast ice movements over periods of hours occurred, this ice action was not significant and usually involved considerable creep components, and low load levels. Once the rubble field formed, mixed modal ice failures were seen around its outer edge. After the formation of the grounded ice rubble, ice pressure panels were installed to monitor ice loads outside the structure. A typical photograph taken during monitoring is shown in Figure 5.17.

The global ice loads that were measured over the winter period are shown in Figure 5.18. The load levels are very low and can be summarized as follows:

- . the largest ice load on the caisson was 30 MN;
- . 85% of the ice loads measured on the caisson were <10 MN;
- . the caisson did not experience any significant local ice loads; or any ice dynamics.

The geotechnical instrumentation indicated that soil deformations, pore water pressures and settlements in the Molikpaq's core and foundation were insignificant. Similarly, caisson deformations and strains were small, while no accelerations were recorded. In summary, the Molikpaq's performance was excellent at the Isserk I-15 deployment location.

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Figure 5.16: Prior to the formation of grounded ice rubble around the caisson and prior to the onset of landfast ice conditions, the moving ice cover failed against the Molikpaq's sloped sides in bending, at low load levels.



Figure 5.17: After the formation of the grounded ice rubble, ice pressure panels were installed to monitor ice load outside the structure.

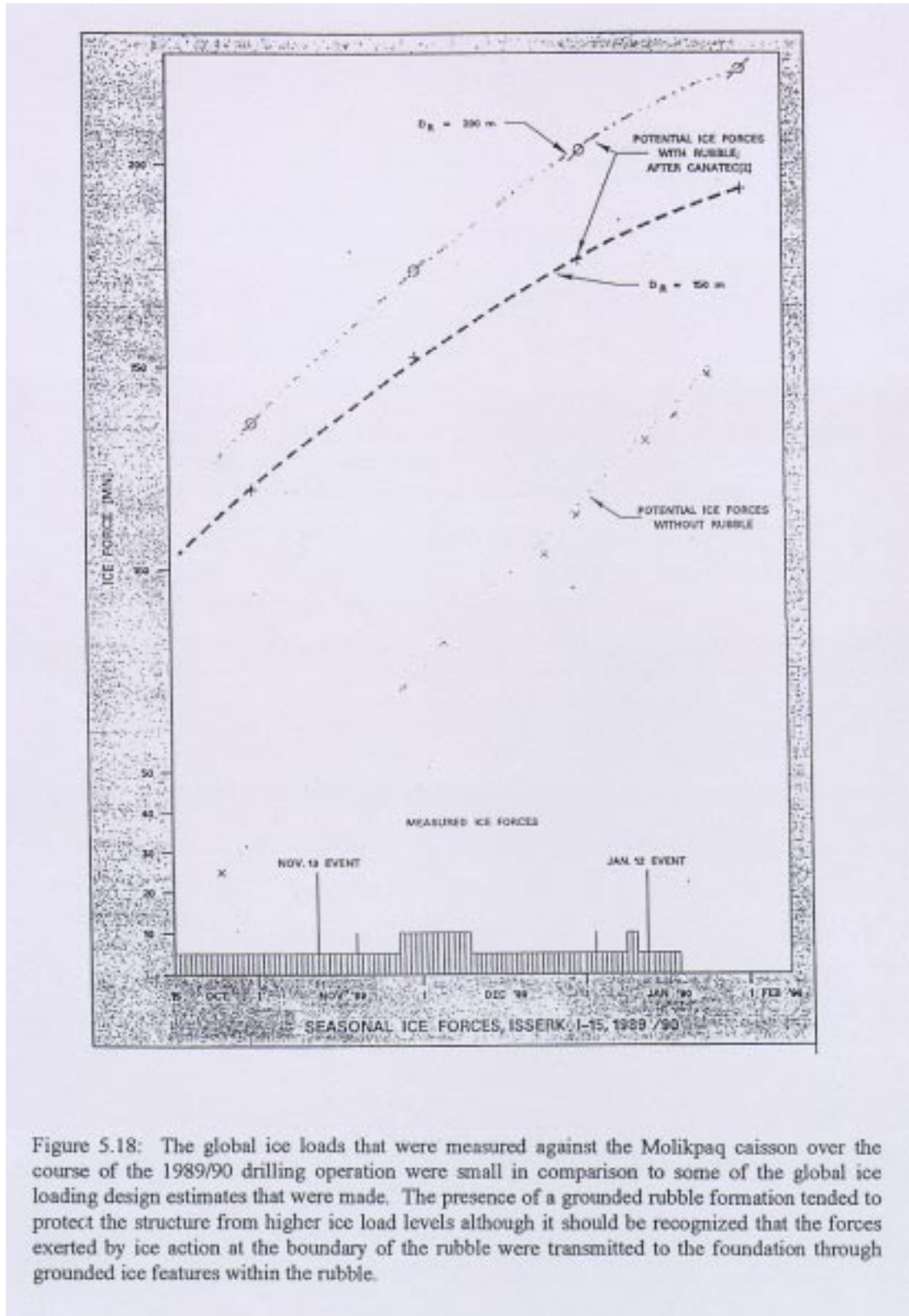


Figure 5.18: The global ice loads that were measured against the Molikpaq caisson over the course of the 1989/90 drilling operation were small in comparison to some of the global ice loading design estimates that were made. The presence of a grounded rubble formation tended to protect the structure from higher ice load levels although it should be recognized that the forces exerted by ice action at the boundary of the rubble were transmitted to the foundation through grounded ice features within the rubble.

### 5.4.3 Deployment Summary

From the perspective of ice loads on the Molikpaq, the key points from the 1989/90 deployment at the Isserk I-15 location are as follows:

- . the Molikpaq was in the landfast ice zone, rather than in moving winter pack ice;
- . the ice interactions that occurred involved thin moving first year ice and slow, limited displacements of thicker winter ice;
- . the Molikpaq's shallower set down draft resulted in sloped walls at the waterline, which caused the ice to fail in bending at relatively low load levels during freeze-up;
- . mid way through the freeze-up period, the Molikpaq's sloped faces acting in combination with its shallow set down draft resulted in the formation of a grounded rubble field around the caisson from thin ice, which protected it from direct ice action over the remainder of the winter;
- . the Molikpaq experienced very low load levels in this landfast ice zone deployment, and did not encounter significant local ice loading or any vibrations associated with ice induced dynamics.

## **6. EFFECT OF FAILURE MODE ON ICE LOAD**

### **6.1 Direct Ice-Structure Interaction Failure Pressures**

Interaction of ice with a near vertical ice-structure interface occurred at both Tarsiut P-45 and Amauligak I-65, and both experiences have been analyzed by Gulf Canada. However, interestingly, the analytical work pursued two different themes:

- at Tarsiut P-45, interest centered on the effect of ice velocity on the failure pressure. This interest was based on the wide range of velocities encountered and the observation that failure pressures seemed quite strongly related to velocity, even during crushing events.
- at Amauligak I-65, interest centered on peak crushing pressure. This interest was based on the identification of phase-locked crushing as the critical ice loading mechanism.

When examined from the perspective of this project, it appears that both seasons have similar ice experience. Specifically, if the data from both seasons are plotted on a peak failure pressure versus ice thickness diagram, Figure 6.1, both show the same trend. One other line has been drawn on the plot and that is the theoretical fracturing pressure relationship based on fracture mechanics. This line having been taken from the research reports on "Ice Crushing" prepared for the National Energy Board by Cold Oceans Design Associates (1993 and 1994). Importantly, the gradient of the predicted pressure-thickness relationship  $-0.25$ , is similar to that found from the Molikpaq field data.

The effect of velocity can be reviewed by choosing particular ice thicknesses, here taken to be 1 m and 10 m, and plotting ice pressure versus far-field velocity as shown in Figure 6.2. Expected ice failure pressures in the creep zone are also shown based on the reference stress method. It is evident that the diagram suggests that failure of a uniform ice sheet is controlled by two competing processes: firstly creep, which then becomes pressure limited by fracture, with a fracture toughness that decreases with velocity. Note that the uncertainty in the initial estimate of fracture toughness by Palmer et al. can now be seen to be explainable in terms of the strain rate used in the fracture toughness testing.

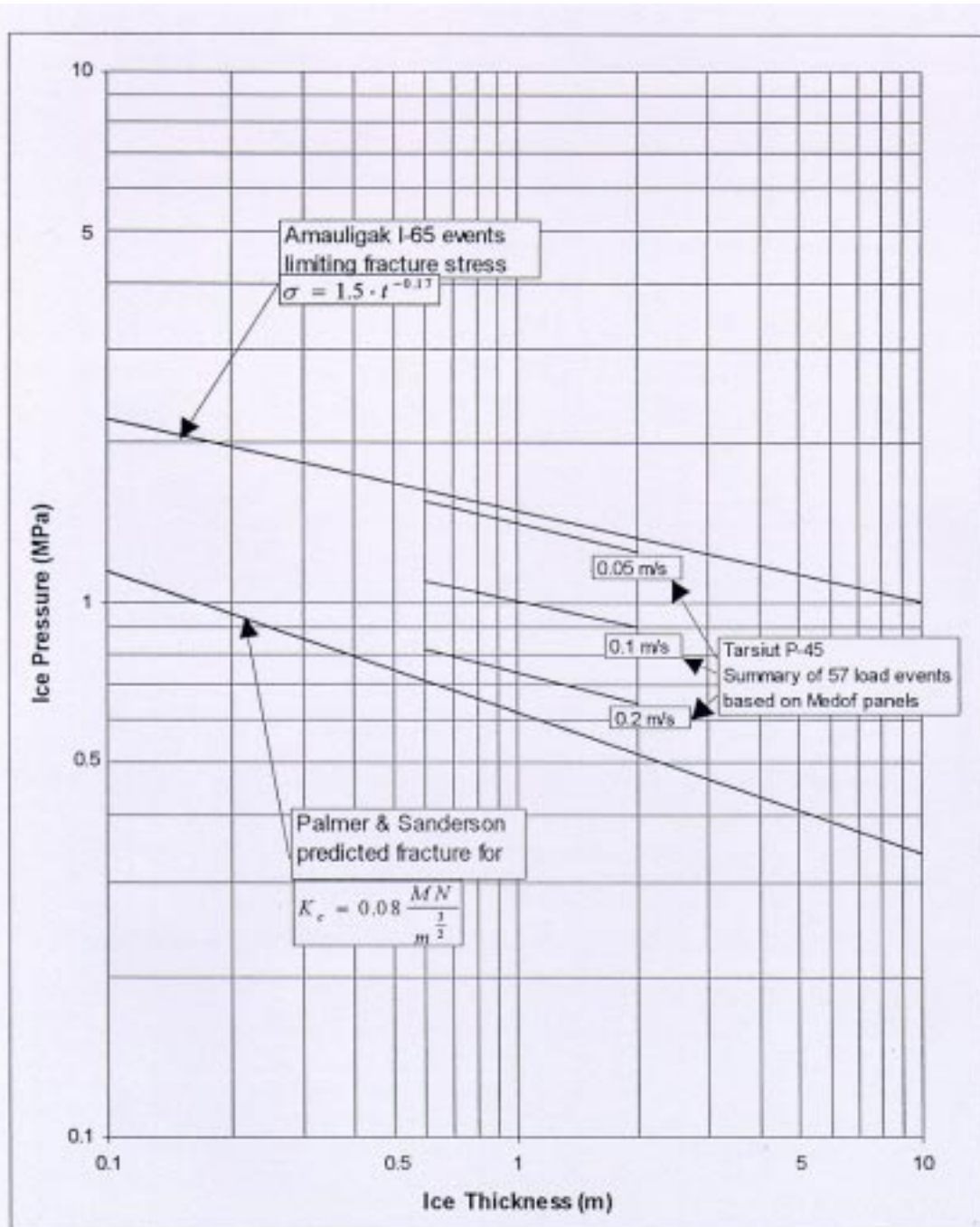


Figure 6.1: Ice thickness versus ice pressure plot for near vertical interface direct interaction with level ice.

2766-rpt.001

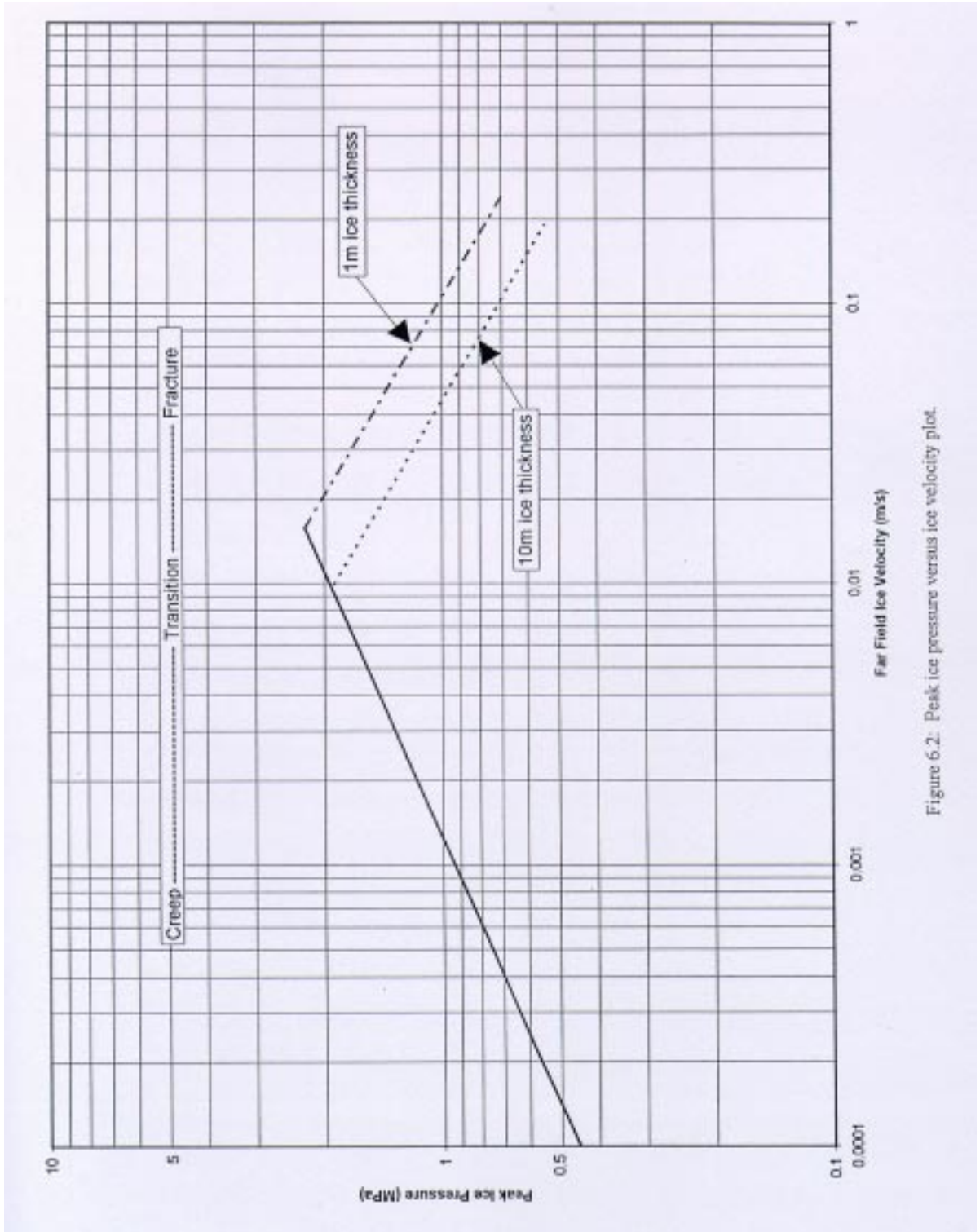


Figure 6.2: Peak ice pressure versus ice velocity plot.

## 6.2 Summary of Molikpaq Experience

The Molikpaq has seen four winter seasons of exposure to Arctic ice, three of which have been in the moving ice shear zone. The ice has ranged from first year ice through to multi-year ice greater than 5 m thick. As experience was gained, the Molikpaq was deployed in different ways so that the four years of data actually encompasses a wide range of conditions and ice-structure interactions.

By way of summary, the following key points can be made:

- . During the Molikpaq's first two deployments in 1984/85 and 1985/86, which involved deep set down drafts and the exposure of near vertical caisson faces at the waterline, grounded ice rubble did not form and as a result, the structure was not protected by rubble and was subjected to direct action from moving ice.
- . Although there were some differences, the Molikpaq's performance in first year ice was consistent and followed the same general pattern. Ice crushing resulted in the highest ice loads while the forces associated with other ice failure modes were relatively small. For first year ice, the maximum crushing loads were in the order of 100 MN.
- . The multi-year ice events that were encountered in 1986 demonstrated that ice loads greater than 200 MN could occur during thick ice crushing. Significant cyclical ice loading was also encountered during simultaneous phased locked crushing events.
- . The Molikpaq's two deployments 1987/88 and 1989/90 involved shallower set down drafts with ice interaction against a sloped face of the caisson. The ice failed predominantly in bending against the caisson, and caused the subsequent formation of grounded rubble fields.
- . These rubble fields protected the structure from direct ice action and as a result, from high global loads, and mitigated local and dynamic ice loading. Bending and mixed modal ice failures did occur at the rubble boundary, but the response at the caisson was negligible.

Perhaps the simplest conclusion that can be drawn from the points summarized above is that grounded, stable rubble piles substantially reduce the ice load on a structure. However, rubble piles must remain in place to ensure lower design ice loads for the deployment. The ability to remain in place would

appear to be substantially affected by berm geometry and water depth. Amauligak F-24 appears to define a transition between what is stable and what is not under moving ice.

Interest in the Molikpaq data tends to centre on ice crushing against a near vertical caisson wall. As reported in the literature, the prevalence of pure crushing and phase-locked (simultaneous) crushing during ice interactions with near-vertical steel was significant. Considerable data analysis and modelling was pursued by Gulf Canada on this topic which established that:

- peak ice pressures during phase-locked crushing were similar to the peak spatially averaged pressures encountered in non-simultaneous failure events;
- crushing-extrusion models can capture the main features of the ice load waveform associated with phase-locked crushed.

The first conclusion, while self-consistent with the idea that peak ice pressures equate to local fracture events in the ice sheet, nevertheless leads to a questioning of "pressure-area" effects. This aspect was examined during the dynamics project which reported that a true scale factor was not pressure-area but pressure-thickness. For the ice crushing events, the relationship of fracture pressure to thickness has an exponent of -0.17.

The Molikpaq data suggests some enhancements are necessary to the crushing-extrusion model initiated during the dynamics project. Specifically, the preliminary ice pressure thickness plot developed for this report illustrates that strain rate is important in determining the fracture stress and defining the transition from creep to crushing. Both of these features are readily added to the crushing-extrusion model. It is important to develop mechanical models of ice loading that captures the full force-time relationship. This is required because the Molikpaq data was gathered in an operational context and because of this is not that complete over the full range of expected conditions.

In addition to extending the crushing-extrusion models, there is a significant amount of data that can be used to address other failure modes and associated failure hypotheses. The Molikpaq datasets provide excellent case histories for testing these hypotheses, and models developed using the hypotheses.

## PERD Research Project Deliverable/Document Data Sheet

Author (s) or Principal Contributor (s)		Completion Date
B.T. Rogers, M. Hardy, M. Jefferies, B. Wright		March 31, 1998
Document/Deliverable Title		
DynaMAC: Molikpaq Ice Loading Experience		
Organization issuing the Document	Number of Pages	
Klohn-Crippen	96 + App	
Sponsoring Agency	File Number	
National Research Council	CHC 14 - 62	
Project Manager/Scientific Authority	PERD Project Number	
Dr. G. Timco	533102	
Notes or Remarks		
Abstract		
<p>The enclosed report and CD-ROM document some of the ice loads exerted on the Molikpaq during its deployment in the Beaufort Sea in 1985/86. The report contains a description of the Molikpaq and its instrumentation, and the CD-ROM contains information on the sensors response during ice loading on the Molikpaq. Use of the information is subject to the restrictions setout by Gulf Canada Resources Ltd.</p>		
Classification	ISBN Number	Contract Number
		CS7-243304-00
	PERD Database Keywords	
	Arctic, Ice_Forces, Molikpaq	

**APPENDIX I**  
**REFERENCE REPORTS AT NATIONAL RESEARCH COUNCIL OF**  
**CANADA**  
**TABLE 14 - FULL SCALE PERFORMANCE MONITORING -**  
**MOLIKPAQ**

Table 14a: Full Scale Performance Monitoring  
Molikpaq

Project	Type	Year	Restriction	Expiry	Priority	Quality
1984/85 Molikpaq Video Review - Second Year Ice Impacts	report	1989	F	1995	H	H
1985/86 Molikpaq Ice Pressure Analysis - Multi-year Events	report	1989	C	1997	H	H
1985/86 Molikpaq Video Review - Failure Mode Assessment	report	1990	F	1995	H	H
Ice & Weather Observations F-24 A & B	report	1988	P	1992	H	H
Ice & Weather Observations I-65 A & B	report	1986	P	1992	H	H
Ice & Weather Observations Isserk I-15 A & B	report	1990	P	1992	H	H
Ice & Weather Observations P-45 A & B	report	1985	P	1992	H	H
Molikpaq Dynamics Project - Phase 1a	report	1988	C	1997	H	H
Molikpaq Dynamics Project - Phase 1b	report	1989	C	1997	H	H
Molikpaq Dynamics Project - Phase 2	report	1991	C	1997	H	H
Molikpaq Performance at Isserk I-15	disk	1990	L	1992	H	H
Molikpaq Performance at Isserk I-15	report	1990	P	1992	H	H
Molikpaq Performance at Isserk I-15	video	1990	L	1992	H	H
Molikpaq at Anauligak F-24	disk	1988	L	1992	H	H
Molikpaq at Anauligak F-24	report	1988	L	1992	H	H
Molikpaq at Anauligak F-24	video	1988	L	1992	H	H
Molikpaq at Anauligak I-65/1985-86	disk	1987	C	1997	H	H
Molikpaq at Anauligak I-65/1985-86	video	1987	C	1997	H	H
Molikpaq at Anauligak I-65/1985-86 Vol. 1	report	1987	C	1997	H	H
Molikpaq at Anauligak I-65/1985-86 Vol. 2	report	1987	C	1997	H	H
Molikpaq at Tarsuit P-45	disk	1986	F	1995	H	H
Molikpaq at Tarsuit P-45	report	1986	F	1995	H	H
Molikpaq at Tarsuit P-45	video	1986	F	1995	H	H

Table 14b: Molikpaq Report Detail

Report	Year
Tarsuit P -45	1985
Vol 1 - Summary	1985
Vol 2 - Environmental	1985
Vol 3 - Geotechnical	1985
Vol 4 - Instrumentation	1985
Vol 5 - Performance Monitoring/Ice Event Data	1985
Event Data Summaries 1984-1985 Vol. 1-57	1986
Ice Interaction/failure Mode Maps	1986
Anauligak I - 65	1986
Phase 1a: Vol 1- Summary of Data Reports	1987
Phase 1a: Vol 2- Deployed Parameters	1987
Phase 1a: Vol 3- Instrumentation	1987
Phase 1a: Vol 4- Ice Force Measurement Validation	1987
Phase 1a: Vol 5- First Year Ice Event Data	1987
Phase 1a: Vol 6- On Ice Investigation	1987
Phase 1a: Vol 7- Multi Year Ice Event Data	1987
Phase 1a: Vol 8- Geotechnical Monitoring	1987
Phase 1a: Vol 9- Environmental Monitoring	1987
Phase 1a: Vol 10-Operational Records	1987
Phase 1a: Vol 11-Errata & Supplementary Information	1987
Summary of Phase 1 Report	1987
Phase 1b: Vol 1 - Main Report	1989
Phase 1b: Vol 2 - Main Report	1989
Phase 1b: App A-Medof/Strain Gauge Calibration Review	1989
Phase 1b: App B-Dynamic Ice Load Models/Literature Review	1989
Phase 1b: App C-BP Ice/Structure Interaction Analysis	1989
Phase 1b: App D-Trashed Ice Lab Test Program (Geotech)	1989

Table 14b: Molikpaq Report Detail

Report	Year
Phase 1b: App E-Sixth Generation Cyclic Ice Load Models	1989
Phase 1b: App F-CICE Analysis of Crushing Mode	1989
Phase 1b: App G-2 dof Lump Mass Interaction Model (Bercha)	1989
Phase 1b: App H-Summary of Review Comments & Response	1989
Phase 2: Vol 1--Main Report	1991
Phase 2: vol 2--Load Measurement	1991
Phase 2: vol 3--Model for Dynamic Behaviour	1991
Phase 2: vol 4--Centrifuge Model Tests	1991
Phase 2: Vol 5--Laboratory Tests	1991
Phase 2: Vol 6--Critical State of Sands & State Influence	1991
Phase 2: Vol 7--Elasto Plastic Model Analysis	1991
Phase 2: Vol 8--Numerical Simulation of Cyclic Triaxial Tests	1991
Phase 2: Vol 9--Reformulation of Alternate Model	1991
Multi Year Ice Event Report - 1986	1986
Dynamic Behaviour of Molikpaq-Prelim Analysis (J.P.Nadreau)	1986
Molikpaq Dynamic Behaviour Model/Bercha Phase 1&2	1987
Molikpaq Dynamic Behaviour Model/Bercha Phase 3&4	1988
Ice Interaction/Failure Mode Maps	1986
Berm Level Survey	1986
Dynamics Project Summary	1991
Dynamic Model of Molikpaq-FE	1986
Added Mass & Damping Coefficients	1987
Event B-Data Summaries Event1 Nov.10/85-Jan.24/86 Vol.5	1988
Event B-Data Summaries Event2 Jan.25/86-Feb.09/86 Vol.4	1988
Event B-Data Summaries Event3 Feb.15/86-Feb.18/86 Vol.3	1988
Event B-Data Summaries Event4 Mar.04/86-Mar.08/86 Vol.2	1988
Event B-Data Summaries Event5 Apr.12/86-Jun.07/86 Vol.1	1988
Event Data Summaries Event1 Nov. 09/85	1988
Event Data Summaries Event2 Nov. 10/85	1988
Event Data Summaries Event3 Nov. 12/85	1988
Event Data Summaries Event4 Nov. 17/85	1988

Table 14b: Molikpaq Report Detail

Report	Year
Event Data Summaries Event5 Nov. 24/85	1985
Event Data Summaries Event6 Dec. 22/85	1985
Event Data Summaries Event7 Jan. 06/86	1986
Event Data Summaries Event8 Feb. 02/86	1986
Event Data Summaries Event9 Feb. 06/86	1986
Event Data Summaries Event10 Feb. 07/86	1986
Event Data Summaries Event11 Feb. 09/86	1986
Event Data Summaries Event12 Feb. 11/86	1986
Event Data Summaries Event13 Feb. 15/86	1986
Event Data Summaries Event14 Feb. 17/86	1986
Event Data Summaries Event15 Feb. 28/86	1986
Event Data Summaries Event16 Mar. 04/86	1986
Event Data Summaries Event17 Mar. 07/86	1986
Event Data Summaries Event18 Mar. 08/86	1986
Event Data Summaries Event19 Apr. 12/86	1986
Event Data Summaries Event20 May. 06/86	1986
Event Data Summaries Event21 May. 12/86	1986
Event Data Summaries Event22 May. 22/86	1986
Event Data Summaries Event23 Jun. 25/86	1986
First Year Event Summaries	1986
WJ Real Time Plots April-May	1986
Anauligak F - 24	1988
Phase 1/Volume 1 Ice Loads Sensors	1988
Molikpaq Performance Review	1988
Phase 2 Volume 1 - Overview Report	1988
Phase 2 Volume 2 - Operational Records	1988
Phase 2 Volume 3 - Environmental Data Report	1988
Phase 2 Volume 4 - Instru. & Data Acquis. Sys.	1988
Phase 2 Volume 5 - Ice Structure Interaction	1988

Table 14b: Molikpaq Report Detail

Report	Year
Phase 2 Volume 6 - Supplementary Studies	1988
Phase 2 Volume 7 - Geotechnical Monitoring	1988
Ice Interaction/Rubble Maps	1988
Ice Movement Monitoring	1988
Isserk I - 15	1990
Ice Force and Rubble Research Study	1990
Environmental Data Report	1990
Operations Report (2 Volumes)	1990
Molikpaq Performance Review	1990
Ice Interaction/Rubble Maps	1990

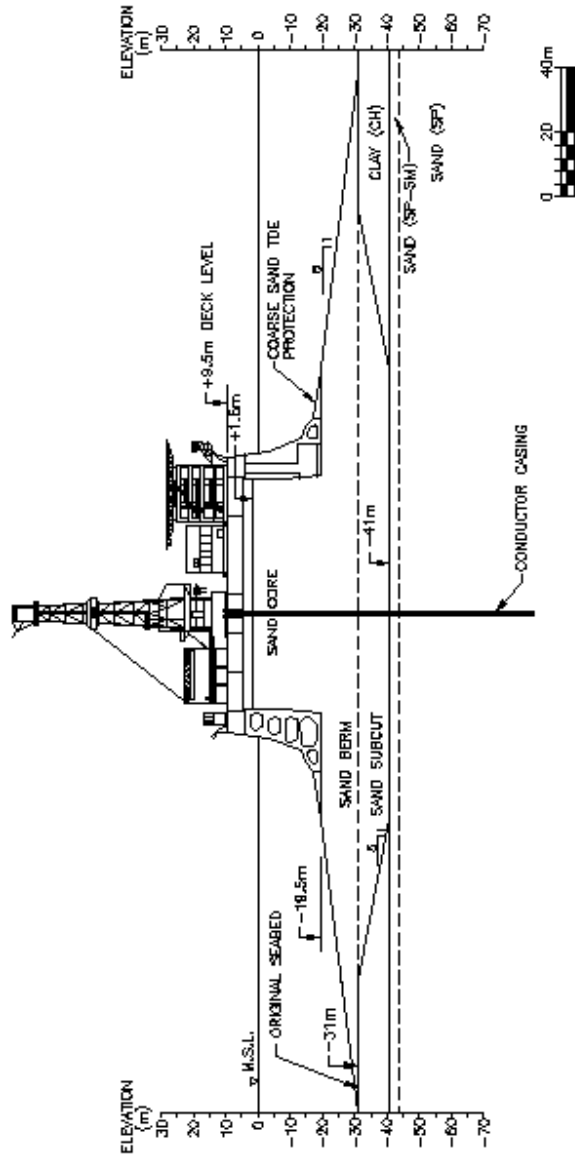
PA 2766 0101

2766-rpt.001

July 18, 1996

**APPENDIX II**  
**AMAULIGAK I-65 SENSOR LOCATION DRAWINGS**

# MOLIKPAQ AT AMAULIGAK I-65 1985-1986

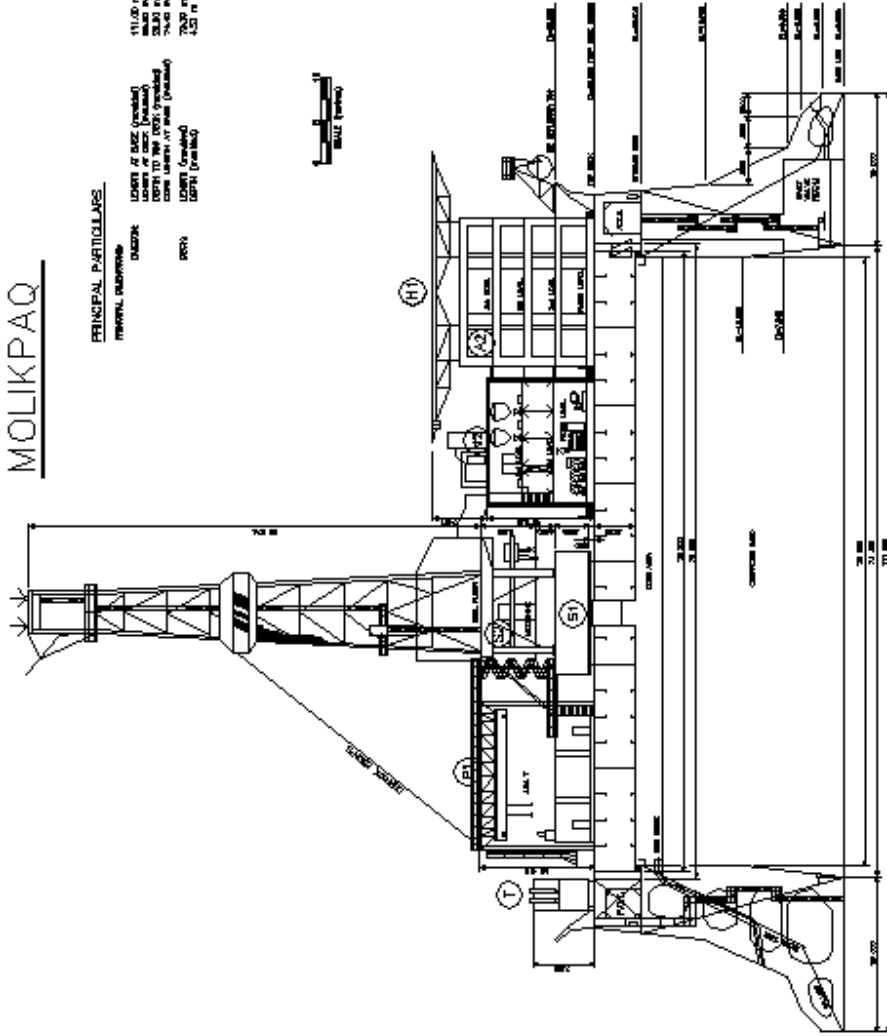


# MOLIKPAQ

## PRINCIPAL PARTICULARS

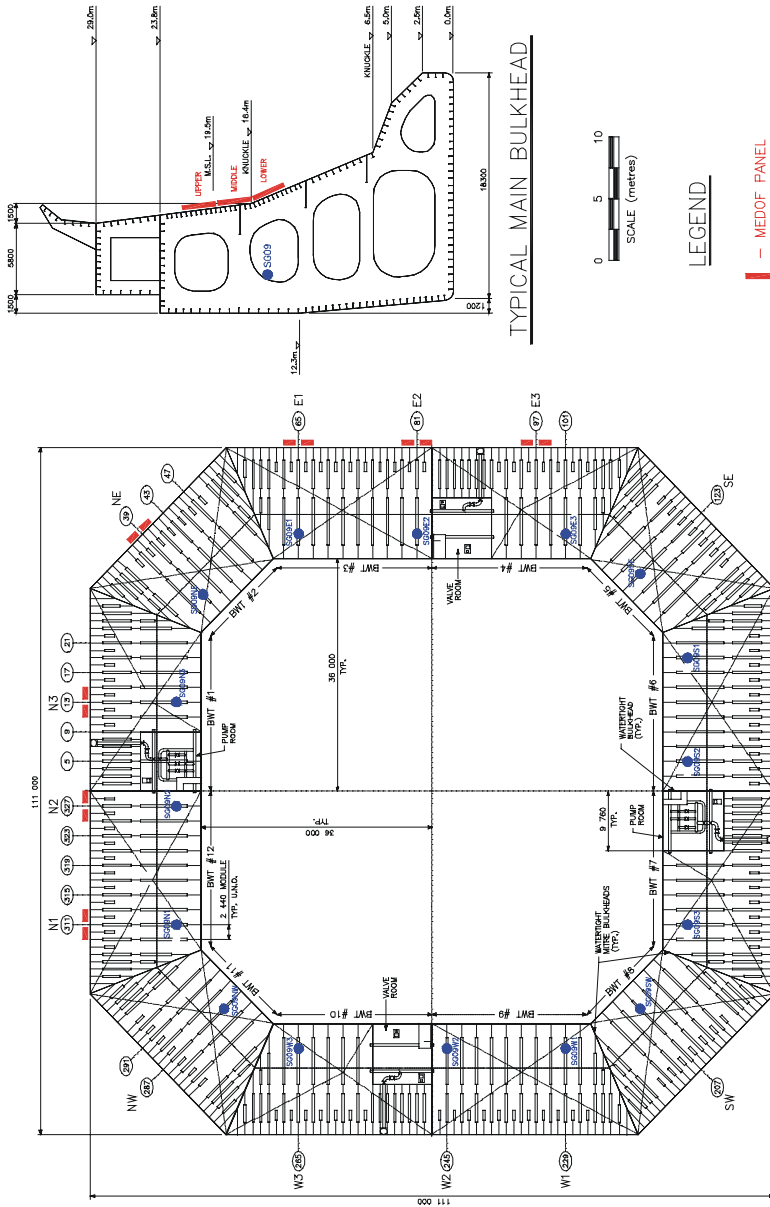
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 LENGTH OF EACH (OVERALL): 11,150 m x 11,150 m  
 WIDTH OF EACH (OVERALL): 11,150 m x 11,150 m  
 TOTAL QUANTITY: 111,000 m<sup>3</sup> x 11,150 m  
 TOTAL LENGTH: 11,150 m  
 TOTAL WIDTH: 11,150 m  
 TOTAL AREA: 124,322 m<sup>2</sup>





# STRAIN GAUGES AND MEDOF PANELS LOCATION PLAN AND SECTION

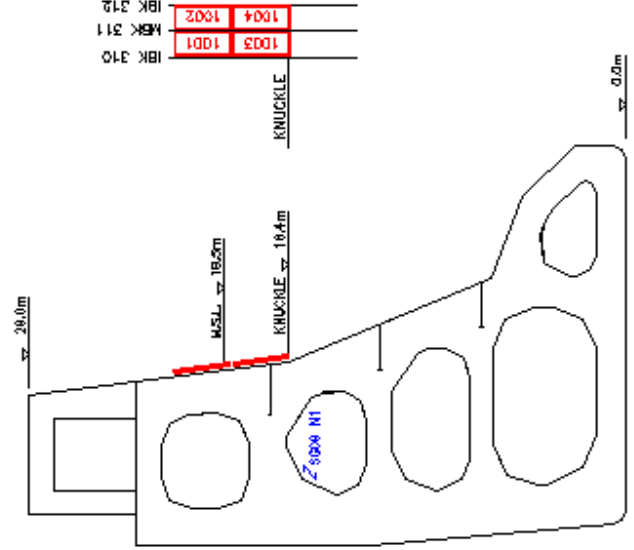


### LEGEND

- MEDOF PANEL
- SG009 STRAIN GAUGE
- E1 MAIN BULKHEAD

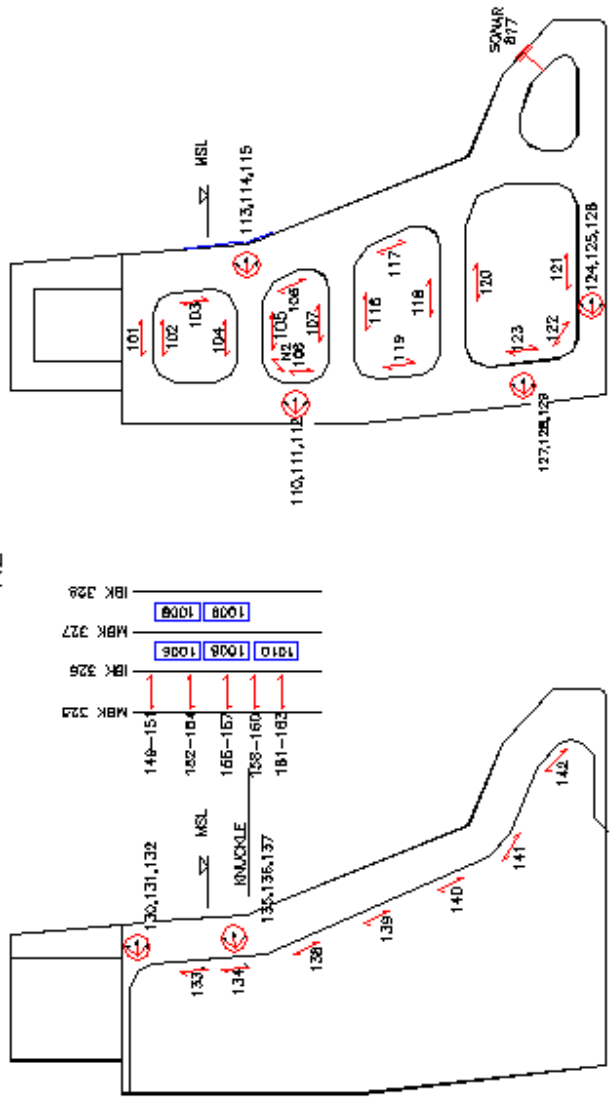
STRAIN GAUGES AND MEDOF PANELS

N1



MAIN BULKHEAD 311

N2



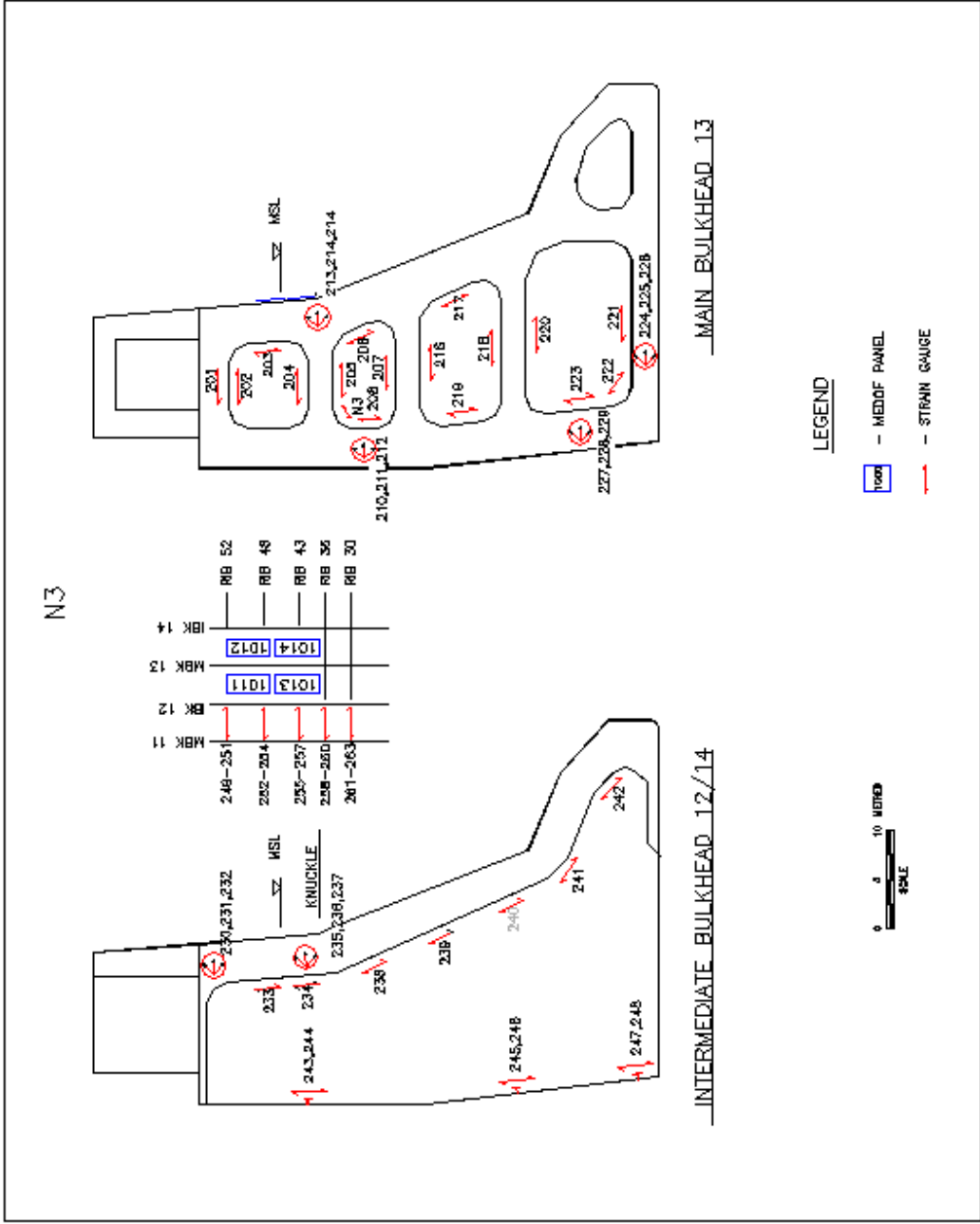
INTERMEDIATE BULKHEAD MAIN BULKHEAD

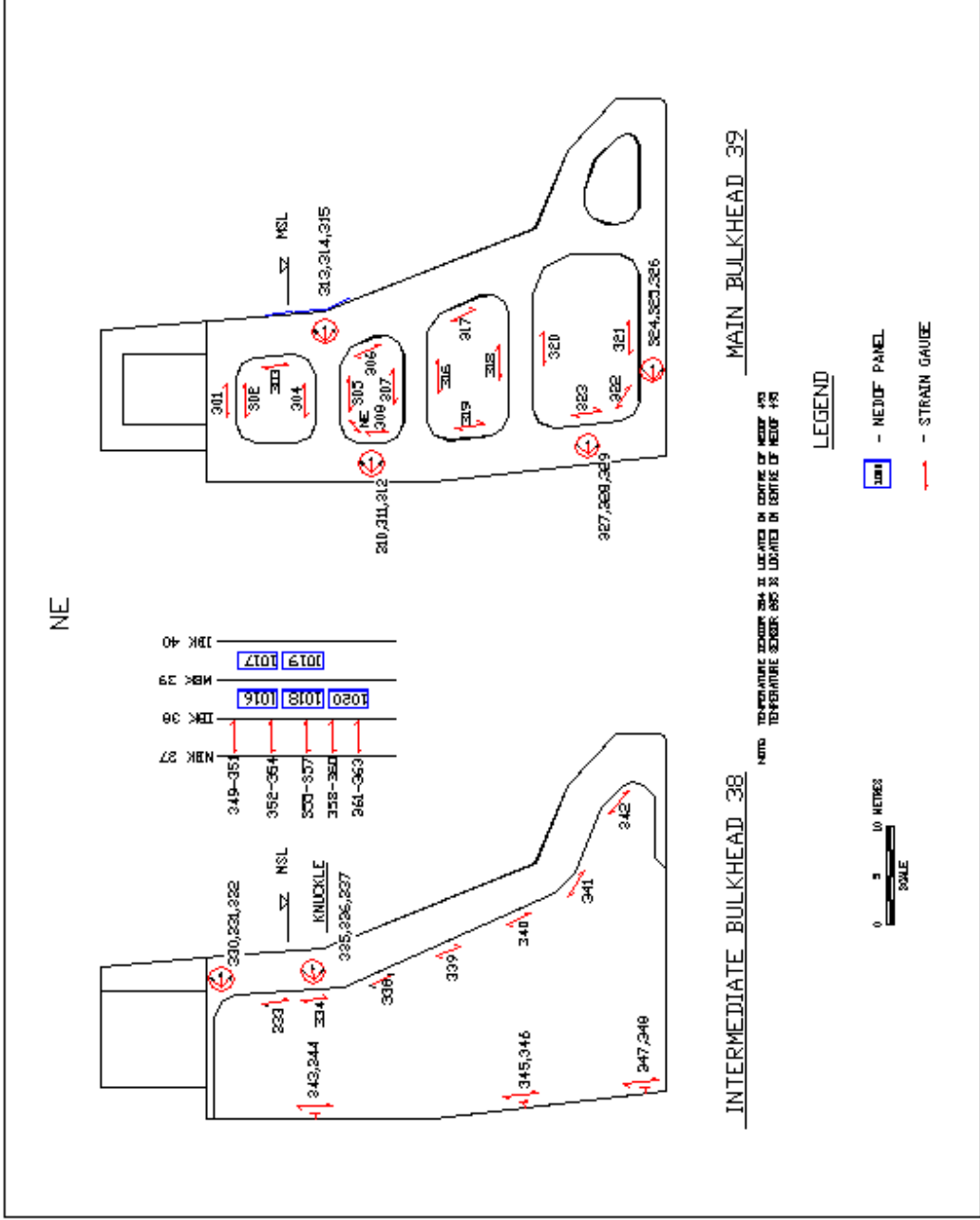
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 TEMPERATURE SENSOR 263 IS LOCATED IN CENTER OF MEDOF 105



LEGEND

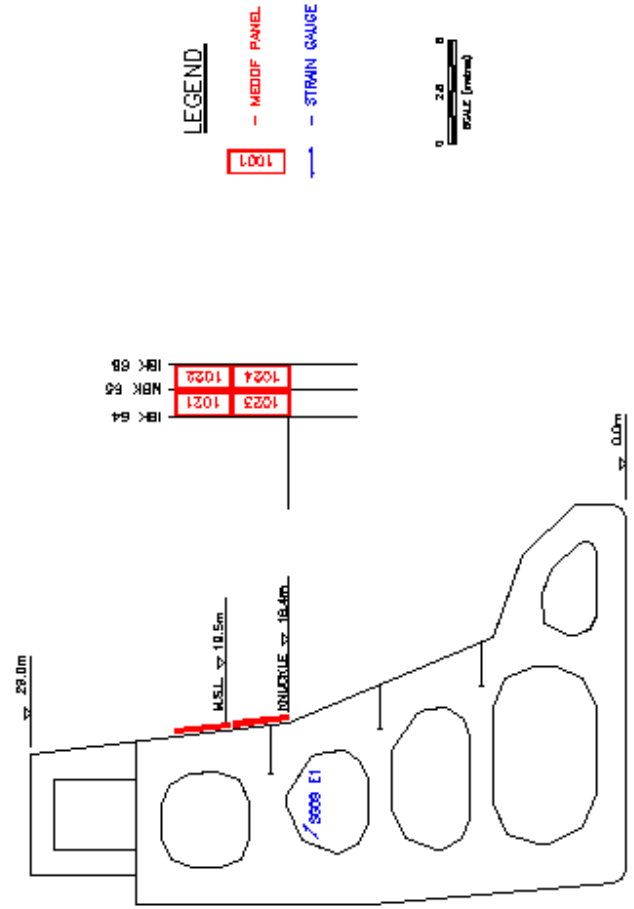
- 1008 - MEDOF PANEL
- - STRAIN GAUGE





# STRAIN GAUGES AND MEDOF PANELS

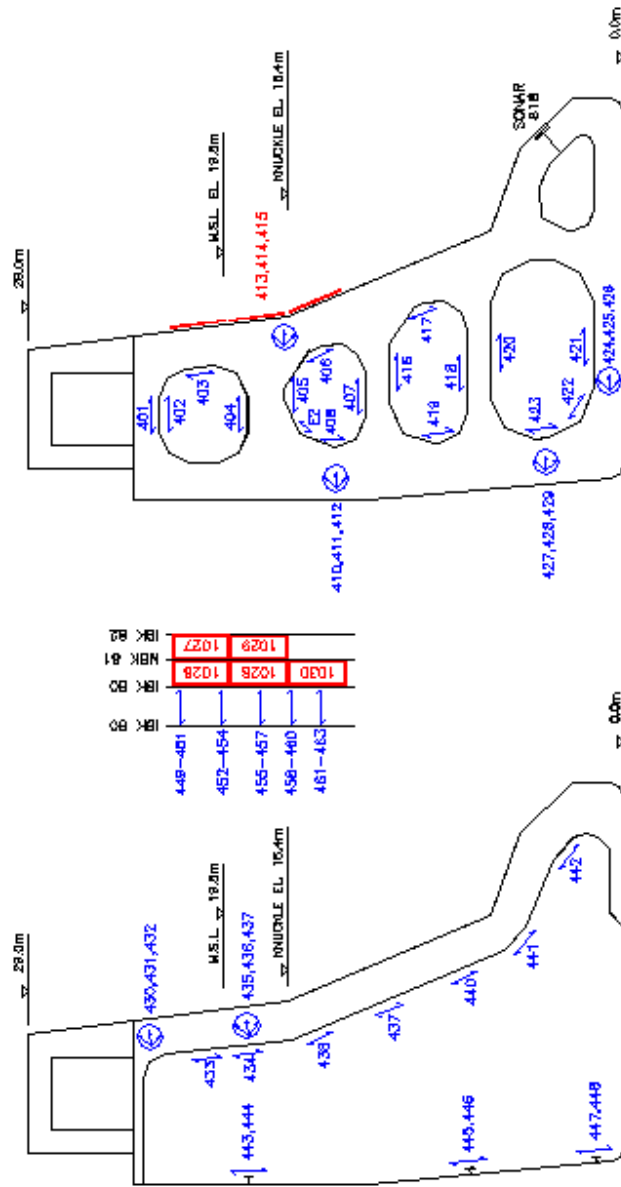
E1



MAIN BULKHEAD 65

# STRAIN GAUGES

E2



MAIN BULKHEAD B1

INTERMEDIATE BULKHEAD 80

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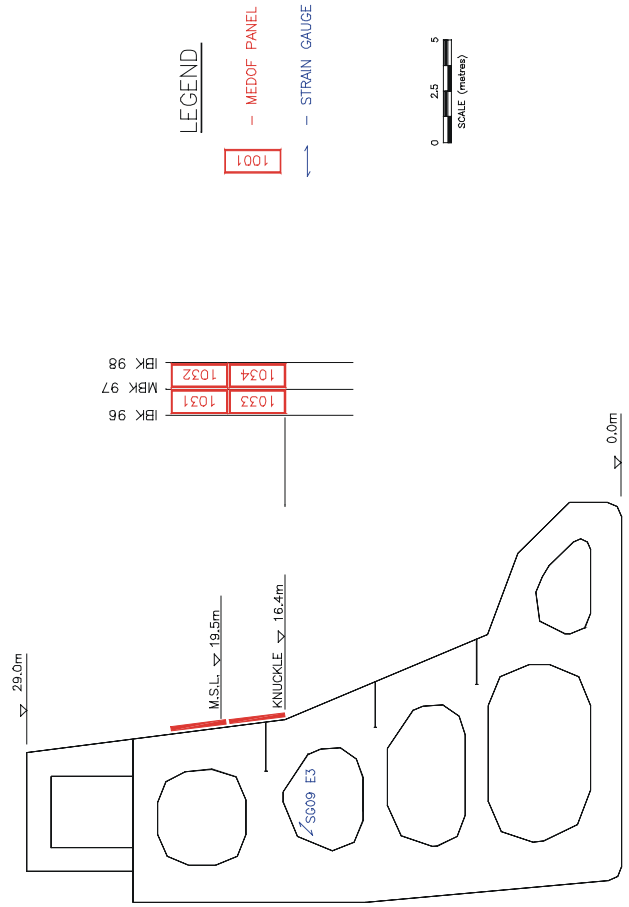
STRAIN GAUGES

MEMOF PANEL



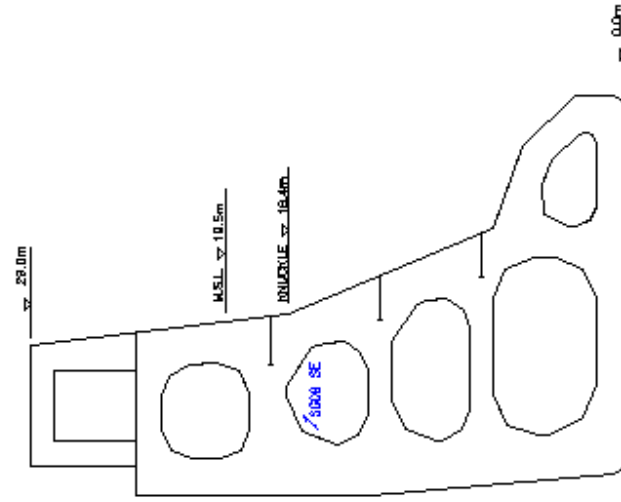
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E3



MAIN BULKHEAD 101

# STRAIN GAUGES SE



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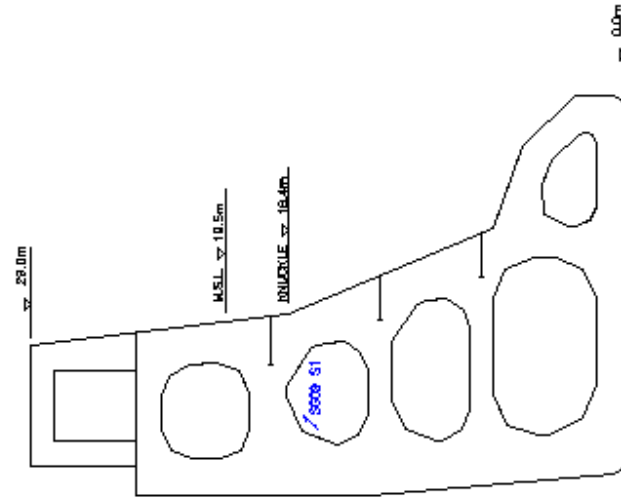
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MAIN BULKHEAD 123

STRAIN GAUGES

S1



MAIN BULKHEAD 147

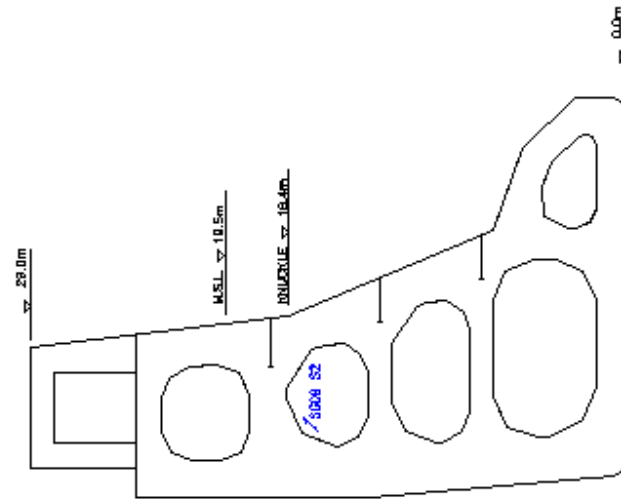
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STRAIN GAUGES

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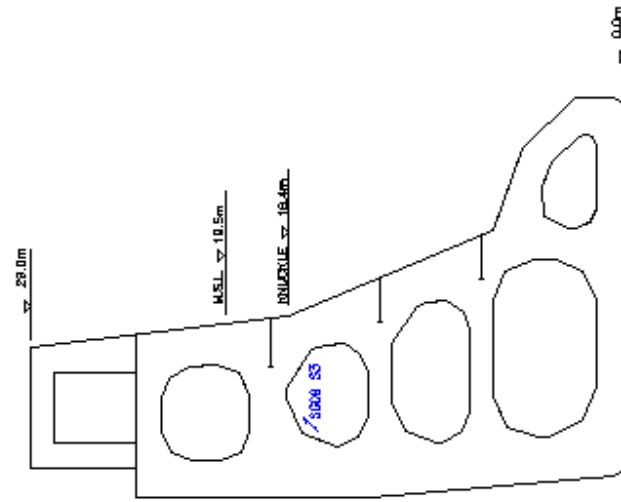
MAIN BULKHEAD 161

LEGEND

— — STRAIN GAUGE



STRAIN GAUGES  
S3



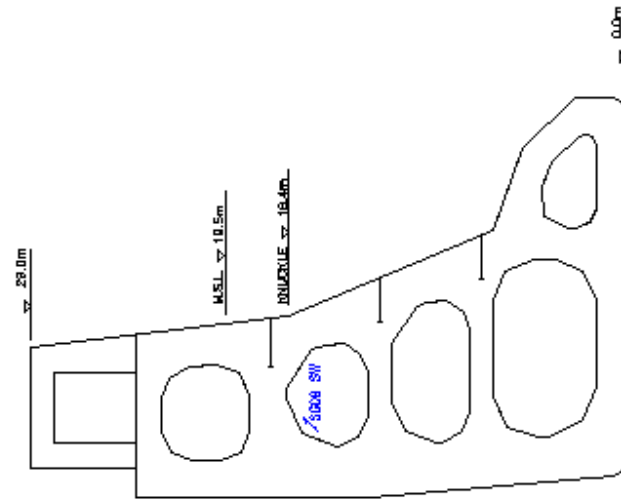
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— — STRAIN GAUGE



STRAIN GAUGES  
SW



LEGEND

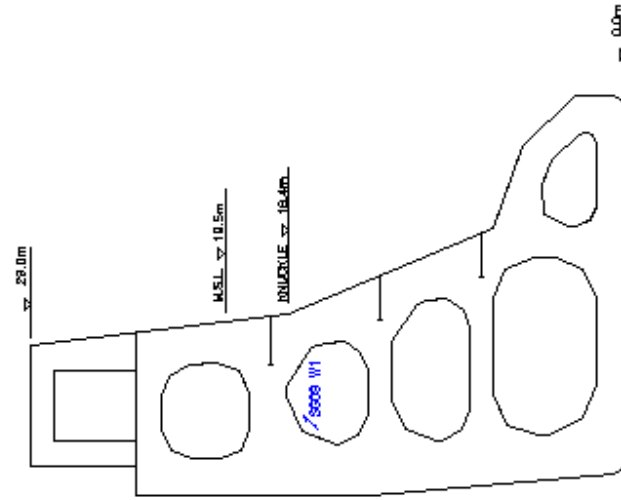
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MAIN BULKHEAD 207

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W1



MAIN BULKHEAD 229

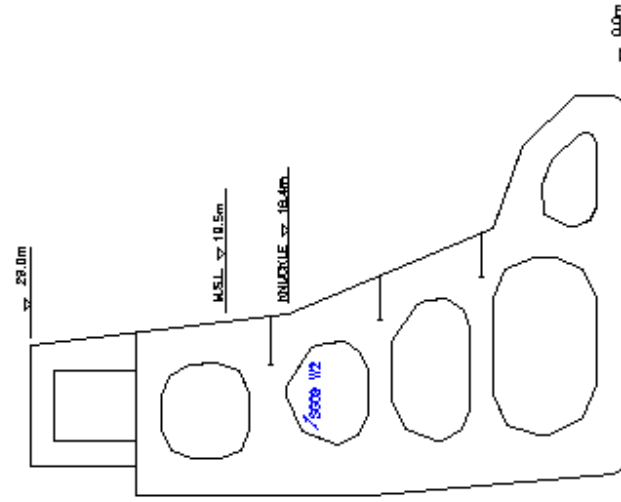
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— — STRAIN GAUGE



STRAIN GAUGES

W2

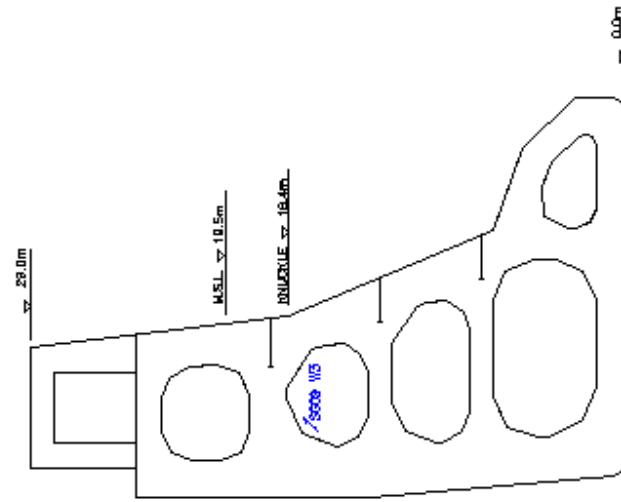


MAIN BULKHEAD 245



STRAIN GAUGES

W3



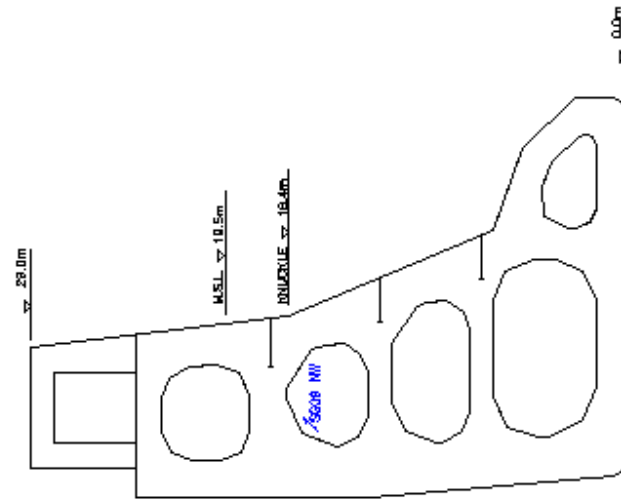
LEGEND

— — STRAIN GAUGE



MAIN BULKHEAD 265

STRAIN GAUGES  
NW



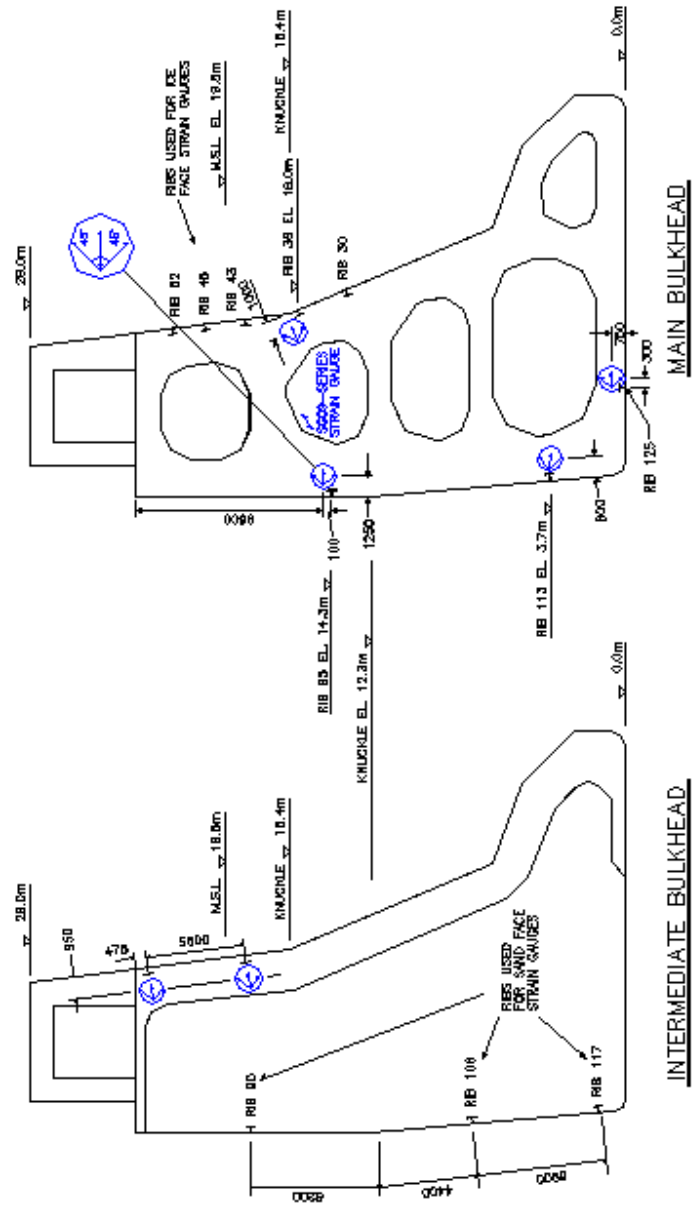
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— — STRAIN GAUGE



MAIN BULKHEAD 287

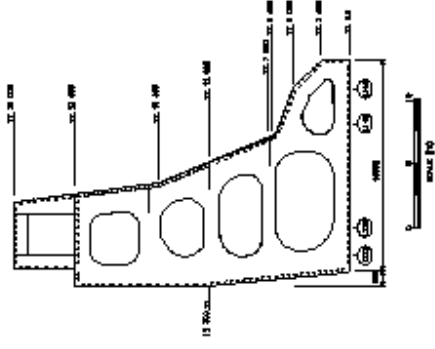
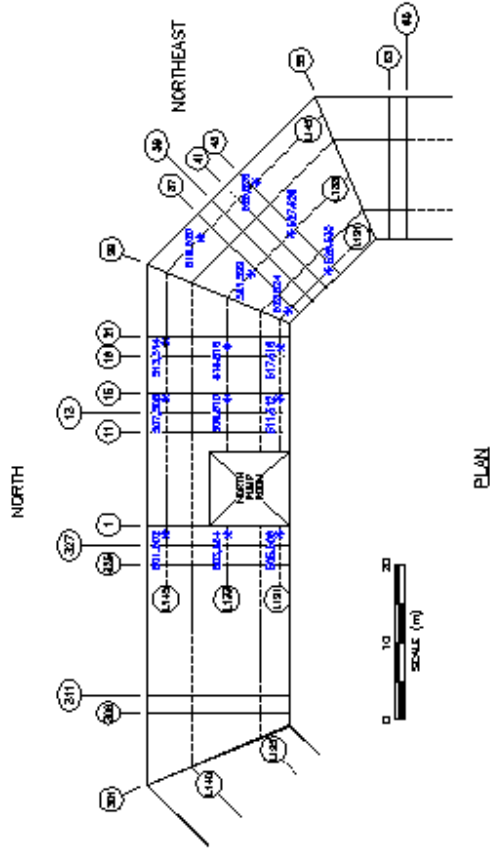
# TYPICAL ROSETTE AND SG09 STRAIN GAUGE LOCATIONS



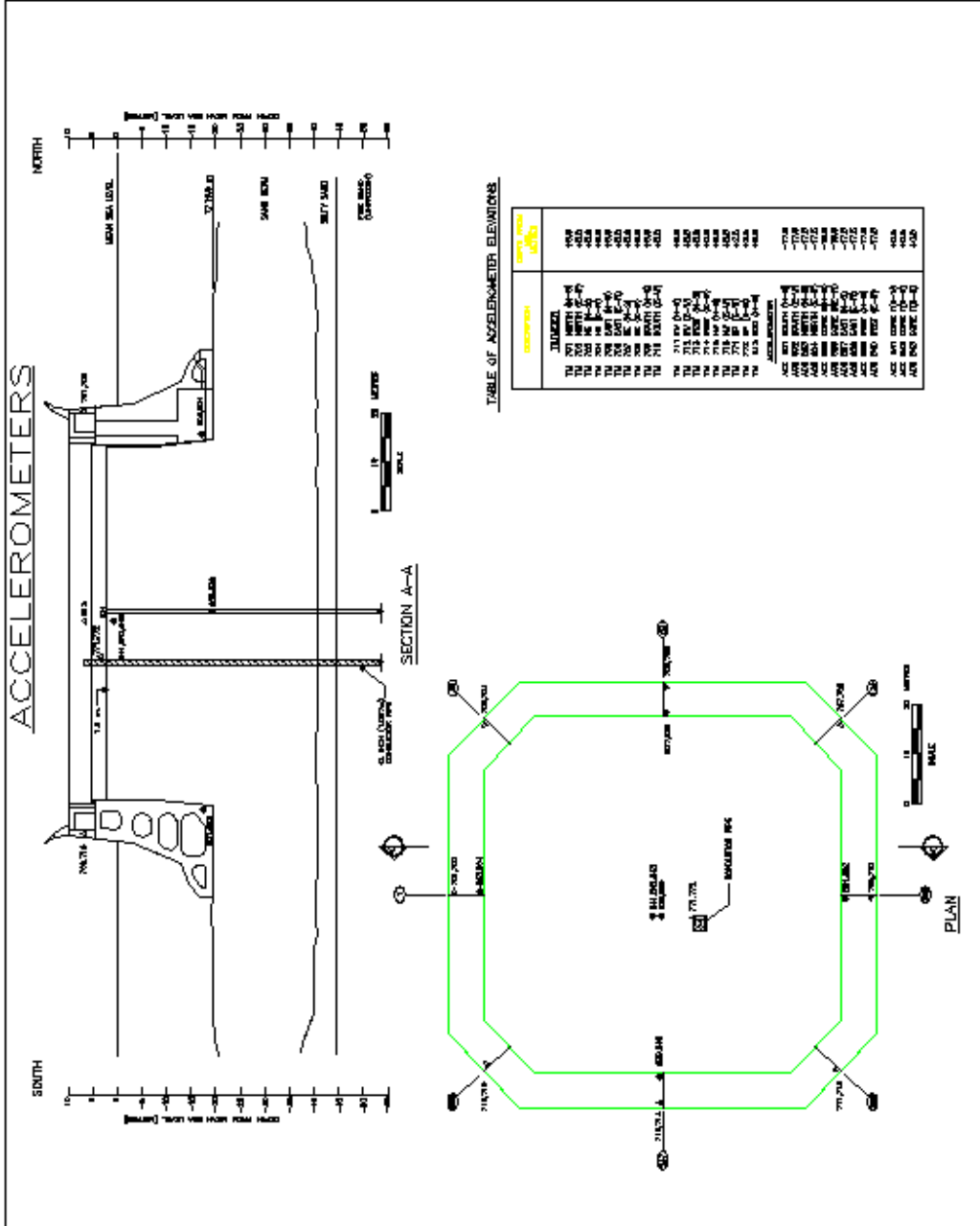
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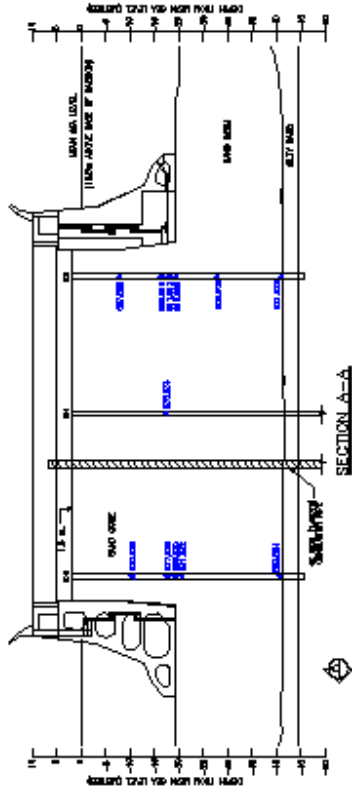
# BASE STRAIN GAUGES







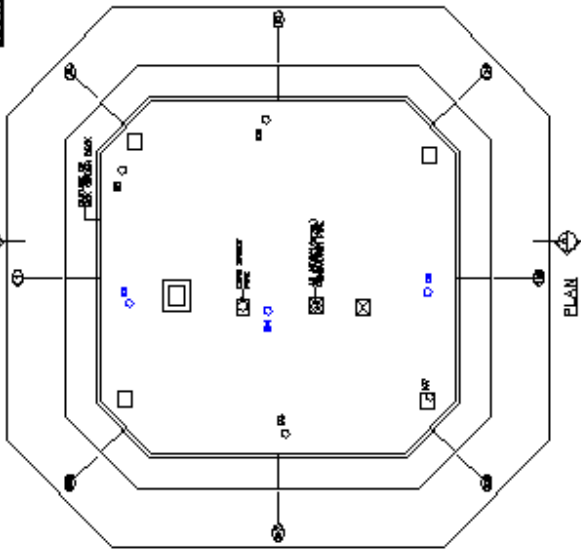
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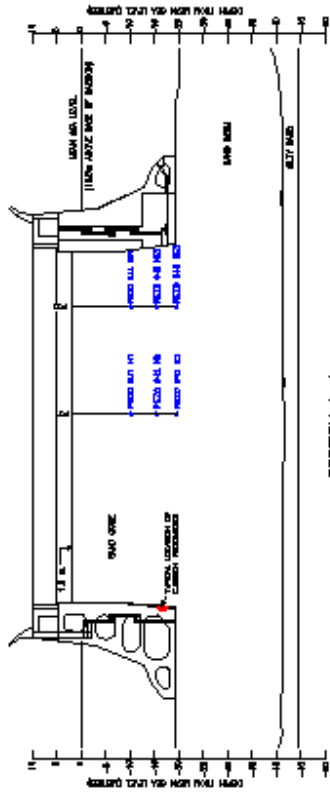
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TABLE OF INCLINOMETER ELEVATIONS

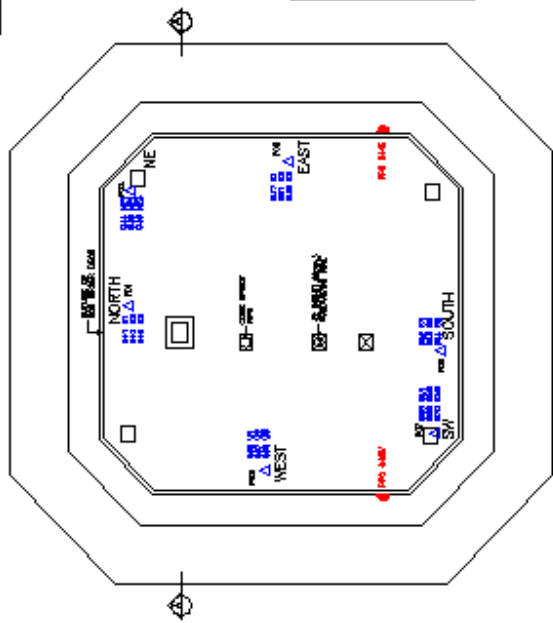
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144	144.00
145	145.00
146	146.00
147	147.00
148	148.00
149	149.00
150	150.00
151	151.00
152	152.00
153	153.00
154	154.00
155	155.00
156	156.00
157	157.00
158	158.00
159	159.00
160	160.00
161	161.00
162	162.00
163	163.00
164	164.00
165	165.00
166	166.00
167	167.00
168	168.00
169	169.00
170	170.00
171	171.00
172	172.00
173	173.00
174	174.00
175	175.00
176	176.00
177	177.00
178	178.00
179	179.00
180	180.00
181	181.00
182	182.00
183	183.00
184	184.00
185	185.00
186	186.00
187	187.00
188	188.00
189	189.00
190	190.00
191	191.00
192	192.00
193	193.00
194	194.00
195	195.00
196	196.00
197	197.00
198	198.00
199	199.00
200	200.00



# PIEZOMETERS



SECTION A-A



## LEGEND

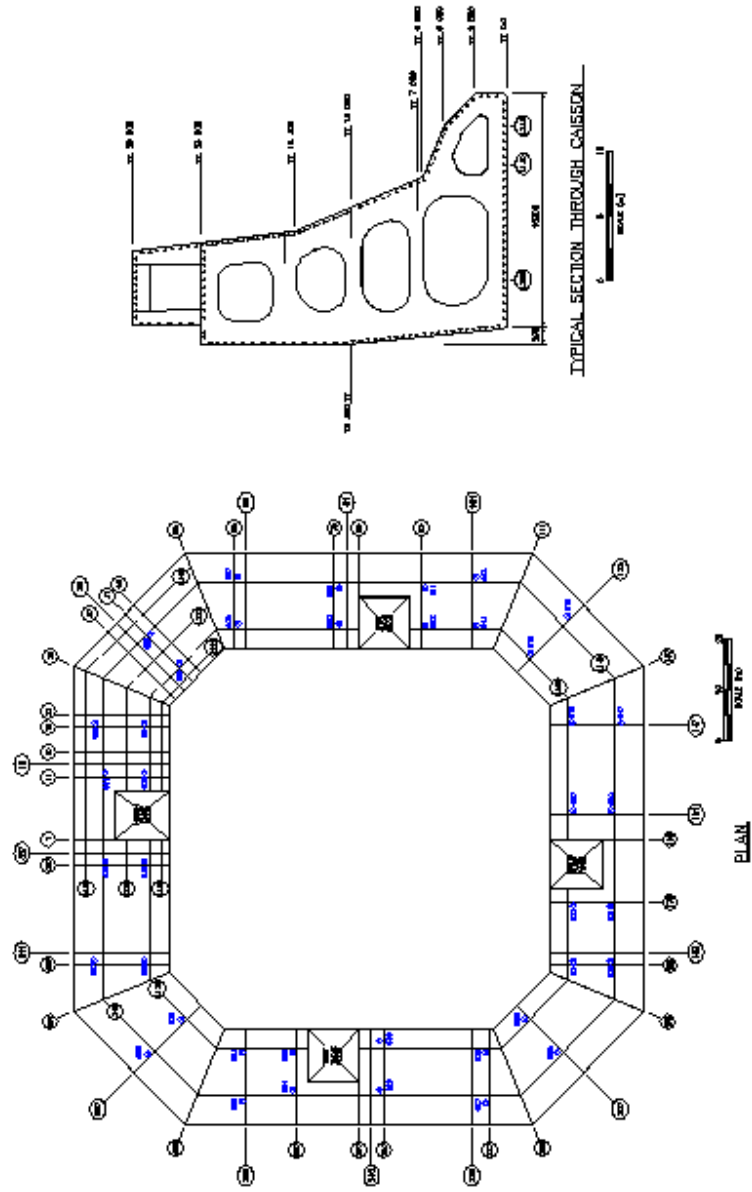
- ▲ PIEZOMETER STRING
- DARSSON PIEZOMETER

TABLE OF PIEZOMETER ELEVATIONS

DESCRIPTION	DEPTH (MM)	DEPTH (M)	DESCRIPTION	DEPTH (MM)	DEPTH (M)
<b>PIE - NORTH</b>					
PIEZO 041 01	1000	1.00	PIEZO 041 01	1000	1.00
PIEZO 041 02	1000	1.00	PIEZO 041 02	1000	1.00
PIEZO 041 03	1000	1.00	PIEZO 041 03	1000	1.00
PIEZO 041 04	1000	1.00	PIEZO 041 04	1000	1.00
PIEZO 041 05	1000	1.00	PIEZO 041 05	1000	1.00
<b>PIE - SOUTH</b>					
PIEZO 042 01	1000	1.00	PIEZO 042 01	1000	1.00
PIEZO 042 02	1000	1.00	PIEZO 042 02	1000	1.00
PIEZO 042 03	1000	1.00	PIEZO 042 03	1000	1.00
PIEZO 042 04	1000	1.00	PIEZO 042 04	1000	1.00
PIEZO 042 05	1000	1.00	PIEZO 042 05	1000	1.00
<b>PIE - WEST</b>					
PIEZO 043 01	1000	1.00	PIEZO 043 01	1000	1.00
PIEZO 043 02	1000	1.00	PIEZO 043 02	1000	1.00
PIEZO 043 03	1000	1.00	PIEZO 043 03	1000	1.00
PIEZO 043 04	1000	1.00	PIEZO 043 04	1000	1.00
PIEZO 043 05	1000	1.00	PIEZO 043 05	1000	1.00
<b>PIE - EAST</b>					
PIEZO 044 01	1000	1.00	PIEZO 044 01	1000	1.00
PIEZO 044 02	1000	1.00	PIEZO 044 02	1000	1.00
PIEZO 044 03	1000	1.00	PIEZO 044 03	1000	1.00
PIEZO 044 04	1000	1.00	PIEZO 044 04	1000	1.00
PIEZO 044 05	1000	1.00	PIEZO 044 05	1000	1.00

NOTE: QUASAR PIEZOMETERS ARE LOCATED 16.0m BELOW NSL.

# TOTAL PRESSURE CELLS



27664204W4