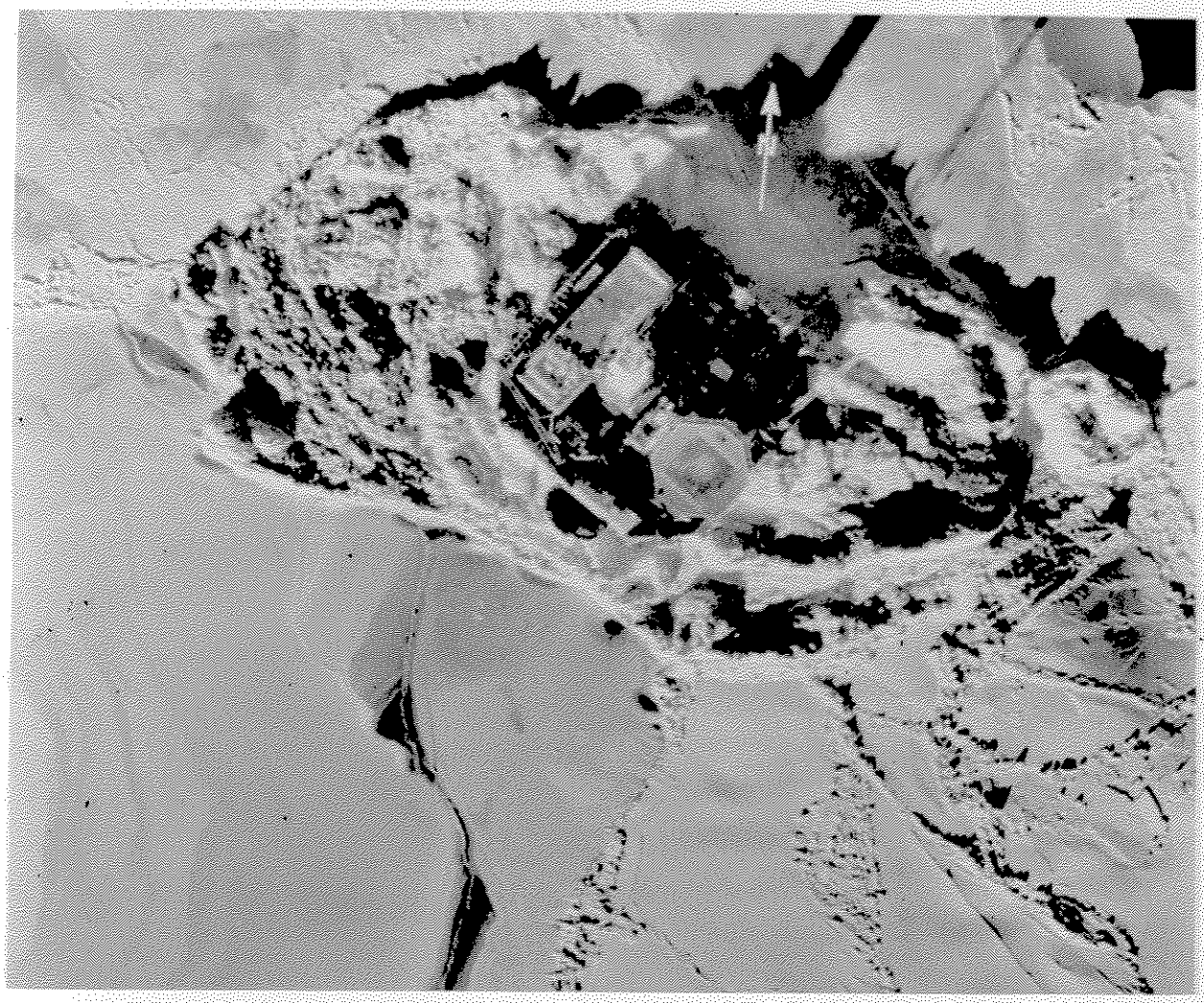

ICE LOADS AND PRESSURES - JOINT INDUSTRY PROJECT

MOLIKPAQ AT AMAULIGAK F-24, 1987 - 88

VOLUME 1: OVERVIEW REPORT

PHASE 2

MAJOR PROJECTS DEPARTMENT
GULF CANADA RESOURCES LIMITED
CALGARY, ALBERTA

MOLIKPAQ AT AMAULIGAK F-24

1987-88

OVERVIEW REPORT

ICE LOADS AND PRESSURES ON THE MOLIKPAQ JOINT INDUSTRY PROJECT

Phase 2, Volume I

GULF CANADA RESOURCES LIMITED

MAJOR PROJECTS, FRONTIER DEVELOPMENT

December 1988

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"The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official polices or recommendations of the Department of the Interior of the United States of America".

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1.0 SUMMARY

The Gulf Canada Molikpaq was deployed during the 1987/88 winter season for delineation drilling at Amauligak F-24. In May 1987, a proposal for a Joint Industry Research Project was developed to obtain full scale measurements of ice loads and pressures in the Beaufort Sea transition zone using the Molikpaq. Industry and regulatory support for this Joint Industry Project was provided by:

- Canadian Oil and Gas Lands Administration (COGLA)
- Minerals Management Service (United States Government)
- Ishikawajima-Harima Heavy Industries Co. (Tokyo)
- Mobil Research and Development Corp. (Dallas)
- Esso Resources Canada (Calgary)/Exxon Production Research Co. (Houston)
- Amoco Production Company (Tulsa)

The project work scope was broadly divided into three parts. Firstly, analyses were performed of the anticipated structural response to ice loading, and a strain gauge based transducer system developed to allow improved measurement of the variation of ice load and pressure distributions on a full-scale Arctic drilling platform. Secondly, additional strain gauges were installed on the Molikpaq and calibrated with a physical load test. Thirdly, data collection of both environmental and ice conditions was carried out from November 1987 through to June 30, 1988.

This overview report provides a summary of the work carried out during the Joint Industry Project. It forms Volume 1 of the Phase 2 report for the project. The remaining Volumes 2 through 6 document the results of data collection during 1987/88. This overview report also covers the work carried out during the analysis of the structural response to ice loading, and the installation of individual strain gauges, which is documented in the Phase I report.

The winter season of 1987/88 at Amauligak F-24 was benign. A grounded rubble pile formed around the Molikpaq in late December 1987, and

remained in position until early May 1988. Supplementary studies were implemented for monitoring the rubble pile in March and April 1988. Multi-year ice fragments, and the main pack ice edge, remained a substantial distance north of the location during the entire season. No significant ice loading was experienced by the rubble field or the drilling platform while deployed at Amauligak F-24.

Although it was a 'non-event' year in terms of understanding ice loadings, the results of various studies indicate that:

a) There is considerable complexity in the correct analysis of strain gauges as a measure of ice loading. Independent external load measurement is required to verify the accuracy of ice load algorithms developed for a strain gauge transducer system.

b) An inclined external ice face appears to result in more flexural failure in first-year ice and a reduction in measured ice load.

c) Development of a stable rubble field will occur during ice/structure interaction in water depths of about 14 metres.

2.0 INTRODUCTION

2.1 Project Objectives

Engineers involved with the design of structures and ships for the Arctic are faced with three general problems:

1) To determine the global ice load.

2) To determine the maximum local contact pressure which can be developed by the ice.

3) To determine the simultaneity of loading across the ice face of the structure.

Global ice loads are required for the design of the overall resistance of offshore Arctic structures. However, local contact pressures are also required to determine plate thickness and secondary stiffener design. Both of these can have a significant affect on feasibility, design, and cost of Arctic structures and ships. A wide range of design criteria have been proposed with little data to verify predictions.

The objective of this Joint Industry Project, titled "Ice Loads and Pressures" was to obtain full-scale measurement of global ice forces acting on the Gulf Canada Molikpaq, at Amauligak F-24, and to determine local ice pressures over areas from 25 to 200 m^2. The data was collected over the 1987/88 winter drilling season. The photograph at the end of Section 2 shows the Molikpaq during testing at Amauligak F-24. In addition, ice thickness was measured by upward looking echo sounders deployed on the ocean floor in front of two faces of the caisson. Meteorological and ice drift observations were also documented.

The Molikpaq had previously been deployed in the transition zone of the Beaufort Sea at Tarsiut P-45 (1984-85) and at Amauligak I-65 (1985-86) and had successfully been used to measure ice-structure

interactions. In particular, during February through May 1986, these interactions had included ice loading from multi-year ice.

A review of the data collected during these ice-structure interactions suggested that a more comprehensive measurement of both lateral and vertical load distribution was required. Ice thickness and drift velocity measurements in real time were also identified as an area to improve the overall quality of the ice loading data.

2.2 Milestones and Participants

The proposal for this joint industry study was developed and circulated in May 1987. The project involved the detailed design of a strain gauge based transducer system to provide global ice load measurement, and local pressure measurements across the North, Northeast and Northwest faces of the Molikpaq with individual "panel" areas of approximately 25 m^2. The design of the load transducer system used a finite element model of the structure as a calibration method to derive the response-to-load relationship (referred to as influence matrices). The actual ice loads were then determined from the measured strains by applying the inverse of the influence matrix.

Procurement, installation and calibration of all equipment for the strain gauge based transducer system had to be completed in August 1987, prior to deployment of the Molikpaq at Amauligak F-24. Therefore, an end of June deadline was set for participation.

Sufficient industry participation was assured at this time, and the Joint Industry Project was initiated on July 6, 1987. Final participation in the project was as follows:

- Canadian Oil and Gas Lands Administration (COGLA) - contact I. Konuk
- U.S. Minerals Management Service (MMS) - contact C. Smith
- Amoco Production Company - contact A. Knapp
- Exxon Production Research Company/
  Esso Resources Canada Ltd. - contact D. Egging/K. Croasdale
- Ishikawajima-Harima Heavy Industries Co. (Tokyo) - contact Y. Kumakura

- Mobil Research and Development Corp. (Dallas) - contact A. Prodanovic/ R. Johnson

A total of 70 Hitec Products Inc. model HBW-35-125-3VR foil adhesive weldable strain gauges were installed on bulkheads in the caisson between August 3rd and 26th 1987, while the Molikpaq was being retrofitted after winterization at Summer's Harbour, N.W.T. During the same period a physical calibration of the ice wall was performed in Water Ballast Tank #1 in the North wall. The calibration (to be used to validate the finite element model of the structure) applied a load of 200 tons to the ice wall in the area of main bulkhead No. 13. This load was repeated at three separate heights and involved two series of linked plates with two hydraulic ram of 100 tons capacity.

The physical calibration tests were completed by August 22, 1987, with successful measurements using the new strain gauges installed in Ballast Tank No. 1. However, at this time, drifting of sensor response was noted on some of the new gauges. This drifting of response progressed to gauge failure.

Continued observations were made of all gauges during the remainder of August and early September. It was noted that symptoms of gauge failure typically occurred within ten to fifteen days after installation, and was associated with the use of a fast cure, polysulphide rubber sealant. It was concluded at this time, and subsequently confirmed, that all of the 50 strain gauges installed using the fast cure polysulphide rubber sealant would fail and that a program of gauge re-installation would be required.

The Molikpaq was setdown at Amauligak F-24 on September 18, 1987. The general arrangement of the Molikpaq at Amauligak F-24, which is located at 70° 03' 17.5" N, 133°37' 48.2" W, is shown in Figure 2.1. This site is approximately 23 n.m from the closest land and the water depth is 32 m. The subsea berm was built to -15.8 m, which was the designed set-down draft of the Molikpaq for this location. This is a significant change from previous deployments of the Molikpaq for which the set down draft was in the 19.5 to 20 metre range. The four upward looking echo sounders were

deployed immediately prior to Molikpaq setdown, and all cabling retrieved through the use of acoustic release buoys prior to core filling operations.

Project initiation meetings with participants were held in Calgary on October 8th and 15th, 1987. At this time the project partners were introduced to the finite element work that had been carried out by Arctec Canada Ltd. using the FESDEC model. A summary was presented of the installation and calibration work carried out in August and September, and the problems resulting from the use of the fast-curing sealant. It was proposed to initially re-install a total of 34 replacement gauges to satisfy the project objectives of global ice load measurement, and local ice pressure measurement/simultaneity of loading across the north, northeast and northwest faces of the caisson.

During October and November the re-installation plan was implemented in two separate visits to the Molikpaq. Eaton Corporation strain tube type gauges were used. The gauges included polyurethane insulated, factory sealed cable to eliminate the need for field applied sealants. At the end of the second deployment, a total of 53 strain gauges on 26 bulkheads around the Molikpaq were intact and operating. The collection of data for the Joint Industry Project then ran from November to June 30th, 1988.

During the winter season all of the remaining strain gauges installed in August, 1987 displayed some form of erratic behaviour. Some of the gauges behaved erratically only intermittently, others however, digressed to failure. The outstanding 16 replacement gauges were installed in August 1988. Six (6) gauges were placed on main bulkheads. Ten (10) strain gauges were installed on the soil face stiffeners within the caisson. Although these gauges cannot be used to measure ice load directly, they lead to an improved ability to use finite element models. Use of these gauges is described in Section 3.4.

Following the build-up of a rubble ice mound around the Molikpaq in late December and early January, additional on-ice studies were proposed to supplement ongoing JIP activities. On-ice work was carried out in March

and April by CRREL, NRC and Canatec consultants to document the rubble pile and monitor any load transfer during ice interactions. All field work was terminated in late April/early May, at the same time as the breakdown of the rubble pile. During this same period, Challenger Surveys Ltd., developed and implemented an Ice Movement Monitoring System. Both this system, and the rubble studies are described in Section 4.2.

A final participants meeting was held in September 1988 to present the results of monitoring the Molikpaq at Amauligak F-24, and review the interpretation of the strain gauge based ice load measurement system.

2.3 Reporting

The reports issued under the Joint Industry Project titled "Ice Loads and Pressures" were divided into two phases. The draft Phase I report was submitted in January 1988 and included:

Phase I - Draft Report issued January 1988

A. Ice Load Measurement Algorithms

B. Independent Calibration of Ice Load Strain Gauges

C. Installation and Commissioning

D. Photographs

Following the submission of the draft Phase I report, a progress meeting with participants was held on January 26th, 1988. The ice conditions to date were presented, together with the methodology for analyzing a typical ice event. The meeting then addressed concerns with the validation and accuracy of the ice load algorithms developed using the FESDEC model. It was concluded that further finite element analysis should be performed to improve confidence in the ice load measurements.

The results of these additional studies were incorporated into the Phase I report, which was re-issued in final form in December 1988 and included:

Phase I - Final Report issued December 1988

1.	Review of Modeling and Ice Load Algorithm Derivation	W.H. Wright
2.	Report on the Installation and Commissioning of the Load Measurement Instrumentation	Arctec Canada Ltd.
3.	Development of Ice Load Measurement Algorithms for the Molikpaq Structure	Arctec Canada Ltd.
4.	Finite Element Modeling of the Molikpaq - Calibration and Algorithm Development	Sandwell Swan Wooster Inc.

The project data collection was completed on June 30th, 1988. The results of monitoring at Amauligak F-24 were collated into a set of seven volumes, as outlined below, and distributed to participants as Phase II of the project.

Phase II

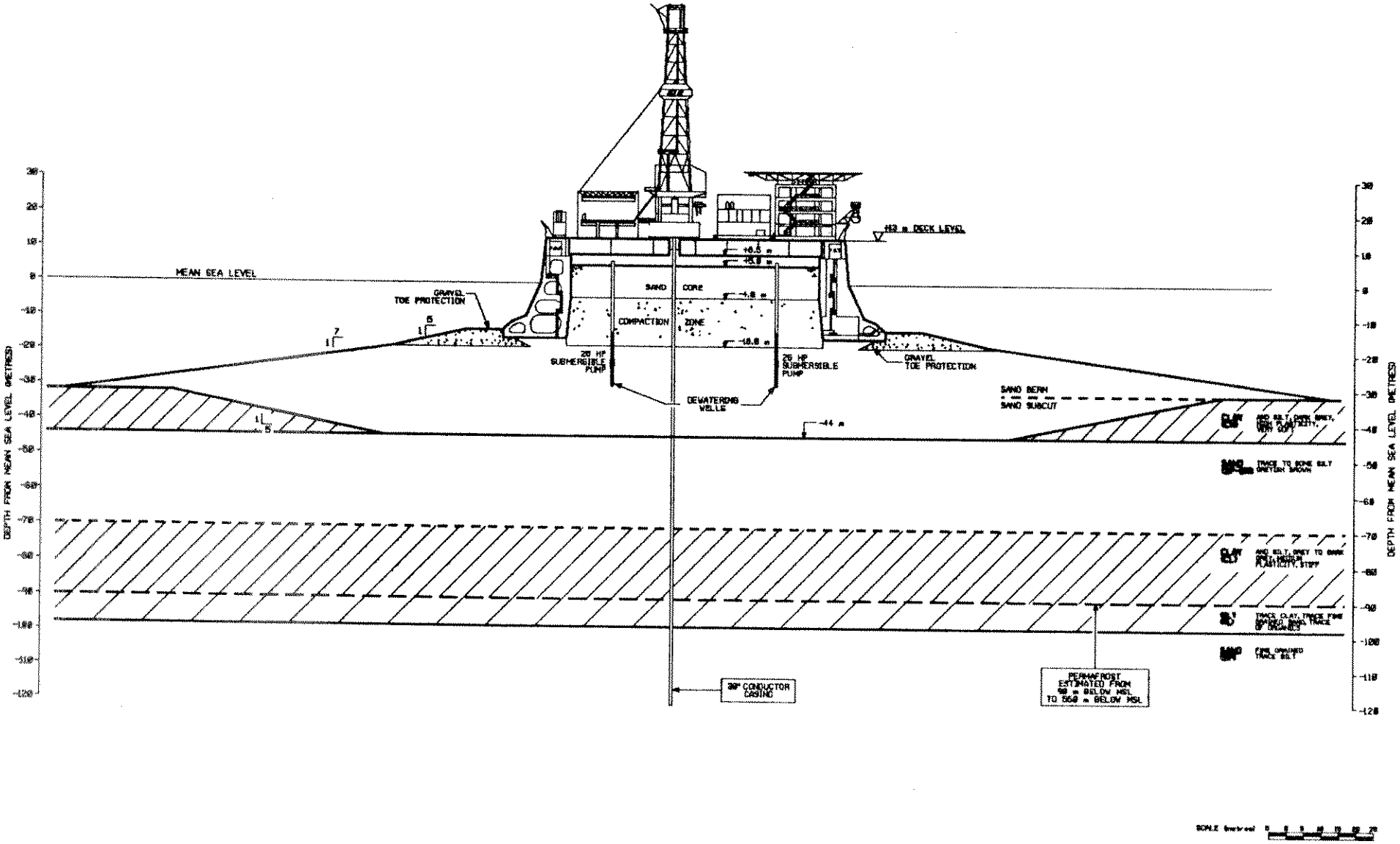
Volume 1	- Overview Report	B.T. Rogers/W.H. Wright
Volume 2	- Operational Records	Stability Team
Volume 3	- Environmental Conditions	Isometrics Consulting Ltd.
Volume 4	- Instrumentation and Data Acquisition	M.D. Hardy
Volume 5	- Ice Loads and Pressures, Ice Structure Interaction	W.H. Wright/W.W. Wells
Volume 6	- Supplementary Studies	
	1. Ice Rubble Field Study	Canatec Consultants Ltd.
	2. Ice Movement Monitoring System	Challenger Surveys Ltd.

This report makes up Volume 1 of Phase II. The contents of all other reports are discussed in Sections 3.0 and 4.0 of this overview report. The detailed results of the CRREL and NRC rubble studies are not included in the JIP reports.

Molikpaq @ Amauligak F-24

Spring, 1988.

FIGURE 2.1
GENERAL ARRANGEMENT
MOLIKPAQ AT AMAULIGAK F-24, 1987-88
CROSS-SECTION



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3.0 MOLIKPAQ AS AN ICE LOAD TRANSDUCER

3.1 Instrumentation

A detailed description of the instrumentation and Data Acquisition System on the Molikpaq can be found in Volume 4 of the Phase II report. The following provides a review of this volume.

The data acquisition system (DAS) on the Molikpaq provides precise quantitative measurements to complement visual observations made in assessing the response to ice loading. Sensors installed on the structure and within the sand core and berm measure both external ice loads and associated structural response. Two data acquisition systems are employed on the Molikpaq: one was installed at the time of commissioning, the other installed after setdown at the Tarsiut P-45 wellsite.

The main data acquisition system uses a Series 200 Hewlett Packard (HP) microcomputer in tandem with two HP6944 multiprogrammers; referred to as the HP200 system. Software control of the data acquisition function allows the system to operate in one of three distinct modes: slow, fast, or burst. Manual and automatic triggers, at preset thresholds, allow the system to change modes appropriate to the level of ice/structure interaction. The second backup system is a hardware controlled Terrascience model SSC-40 that operates at a fixed preselected scan rate. Data is stored onto a 9-track tape in sequential binary format.

Instrumentation employed on the Molikpaq falls into one of three categories: 1) permanently installed and monitored by the DA system, 2) installed subsequent to setdown and monitored by the DA system, and 3) manually measured instrumentation. The data acquisition has a nominal capacity of 576 channels of which approximately 400 are connected to active instrumentation. All 576 channels are continuously monitored by the DA system.

Five minute averages on the 576 channel slow scanner of the HP200 system provide general trends in sensor response on a daily basis. An

operator-selectable scan rate (0.1 to 4 Hz) on the fast scanner provides time-coincident response over a limited period of time (1 hours at a 1 Hertz scan rate). The burst scanner operates at 50 Hertz on a subset of 192 channels to capture the characteristic frequency response during dynamic loading. All data is stored on Winchester discs which are periodically offloaded onto either Bernoulli disc or 1/4 inch tape cartridges.

As all data collected on both systems is stored as raw voltages, several tables of channel descriptions are maintained containing the conversion coefficients for the corresponding engineering units. Data from the HP200 system initially collected into 'Daily' files is compressed into 'Weekly' 'Monthly' and 'Season' summary files to observe longer term trends and to monitor sensor performance.

Permanent instrumentation includes ice pressure panels (30) deployed on the North, Northeast, and East caisson faces measuring ice loads directly by fluid displaced between thin steel plates. Strain gauges (220) measuring structural steel strain were installed on the main and intermediate bulkheads, caisson base plates, ice face ribs and along the caisson sand face. Extensometers (10) installed on all eight caisson faces provide a measure of relative movement between the floating deck and caisson. A pair of deck mounted extensometers measure deck movement relative to the 'stationary' conductor casing. Biaxial accelerometers (26) are mounted midpoint atop each caisson, in the bottom of the Pump/Valve rooms, and in the centre of the box girder deck. Both static tilt and horizontal accelerations are measured to give some indication of the vertical and horizontal acceleration profiles. Water level gauges provide real time monitoring of ballast tanks (12) and draft levels (4). Total pressure cells (40) distributed over the entire caisson base provide an indication of hull overstressing/overturning during setdown and ice loading. Temperature sensors (6) embedded in the caisson face behind the Medof panels are utilized for temperature correction of ice load response.

Instrumentation in the second category includes electric piezometers (23) installed into the sand core and berm to monitor pore

water pressures. In-place inclinometers (20) deployed at the interfaces between core, berm, subcut, and seabed are used to monitor relative horizontal displacement. One triaxial accelerometer buried at the top of the core measures the propagation of vibrations into the core. A biaxial accelerometer deployed down the central inclinometer casing assesses vertical attenuation of vibrations.

The third category of manually read instrumentation includes two dual purpose telescopic settlement casing strings (13 couplings) with integrated water pressure measurement ports (45). Settlement plates (6) embedded into the core surface in conjunction with the settlement casing provide a method for measuring the lateral distribution of compaction in the core and the vertical settlement. One thermistor string lowered into the settlement casing monitors temperatures in the core, berm, and subcut. Manual inclinometers provide a continuous profile of horizontal deflections in each of the six inclinometer casings in the core. Four slow-scan video cameras record ice interactions from video cameras located at up to eight positions on the ice rubble, in the core and along the caisson outer wall. A hand-held video camera may be used to record ice interactions from a variety of angles.

In the context of this Joint Industry Project, measurements of ice loads were obtained from Medof panels and strain gauges. The measurement of ice thickness was obtained from upward looking sonar units, and visual observations. Due to the setdown draft for the Molikpaq of 15.8 m at Amauligak F24, only 3 Medof panels were in a position below the mean sea level to monitor loads. Of these panels, the response from the North panel gave suspect readings. Therefore, ice load measurement were obtained from the response of the 53 "JIP" strain gauges installed on main bulkheads, as shown in Figure 3.1. Other strain gauge responses were available to assist in defining Molikpaq response to ice loading.

The position of the four upward looking sonar units deployed in September is shown in Figure 3.2. Only the sensor in the far west position gave reasonable results. An example of this data is shown in Figure 3.3. (All figures are included at the end of each section).

3.2 FEM Models and Ice Load Algorithms

The full description of the development work carried out on ice load algorithms is presented in the Phase I report. No single load measurement algorithm is recommended at this time due to the absence of a satisfactory calibration which simulated ice loading, the lack of load measurement panels below mean sea level, and the non-occurrence of significant events during the data collection. However, a summary of the algorithm descriptions developed using the FEM models is given in Table 3.1. This section outlines these algorithms.

Arctec was involved as the main contractor in the joint industry study. Prior to installing any new strain gauges, Arctec developed a finite element model of the structure using FESDEC which consisted of a one-quarter global model with a single, fine-mesh main bulkhead (MBK) encompassed within the global model. This model was exercised using point loads at various elevations down the front of the fine-mesh MBK. The strain responses at several potential strain gauge locations were extracted from the model for the various heights of applied load. Thus, vertical influence curves for the potential gauge sites were determined.

Initial attempts to reproduce strain gauge response for the various calibration load cases with the finite element models resulted in a poor agreement. Refinement of the models in order to improve the agreement were therefore initiated. The combined MBK-global model increased in size and complexity as refinements were made. The fine-mesh MBK model was therefore stripped from the global model, with the intent that refinements could be made with greater economy. Boundary conditions could also be extracted from the global model for virtually any bulkhead location to be imposed on the now-separate MBK model, thereby providing greater flexibility of the two models.

Refinements to the fine-mesh MBK model are described in the Arctec report titled "Development of Ice Load Measurement Algorithms for the Molikpaq Structure", presented in the Phase I report. The changes lead to an overall improvement in the agreement between measured and calculated

TABLE 3.1
SUMMARY OF MOLIKPAQ LOAD MEASUREMENT ALGORITHMS

ALGORITHM DESCRIPTION	DERIVATION OF VERTICAL INFLUENCE CURVE	BULKHEAD TREATMENT	CALIBRATION METHOD
1. "Arctec" 3x3 Matrix	Arctec-FESDEC	Ideal	-
2. "SSW" 3x3 Matrix	SSW-Abaqus	Ideal	-
3. C16 Strain Gauge Factor	-	Ideal	Deballast Test
4. Actual:Ideal Refined 3x3 Matrix	Arctec-FESDEC	Individual	Deballast Test
5. FEM Refined 3x3 Matrix	Arctec-FESDEC	Individual	Deballast Test
6. C10 Strain Gauge Factor	SSW-Abaqus	Individual	Deballast Test
7. C10 Strain Gauge Factor	-	Individual	Medof Panels

Notes:

1. Original Arctec 3x3 Influence Matrix
   * not bulkhead-specific
   * Used on Molikpaq during 1987-88 season for calculation of daily peak load.
2. 3x3 Matrix Based on Swan Wooster study
   * single matrix (i.e. not bulkhead-specific)
   * result of simplistic derivation and intended for comparative calculations only.
3. C16 Strain Gauge Factor
   * single gauge factor (not bulkhead-specific)
   * believed to calculate over-predicted ice loads.
4. Actual:Ideal Refined Arctec Matrix
   * bulkhead-specific matrices
   * accurately calculates deballast loads and presumed accurate for wave loading.
   * the only algorithm which has been verified to accurately calculate a load of known magnitude
   * results of the Swan Wooster study suggest this algorithm may over-predict ice-induced loads.
5. FEM-refined 3x3 Arctec Matrix
   * bulkhead-specific matrices
   * believed to be the most accurate algorithm for ice-induced loads however, this has not been confirmed with actual data.
6. C10/SSW Strain Gauge Factors
   * derived using results of Swan Wooster finite element model for C10-319 and data from deballast testing to obtain bulkhead-specific gauge factors
   * believed to be accurate for ice of up to 5 metre thickness however, this has not been confirmed with actual data
7. C10/Medof Strain Gauge Factors
   * bulkhead-specific C10 gauge factors derived from cross-correlation of C10-39 and Medof panel #1020
   * highly suspect due to low level of loading experienced during time period used in correlation.

strain gauge responses. Arctec then developed an influence matrix for the C16, C10 and C6 group of gauges for an "ideal" bulkhead. (Algorithm 1, Table 3.1).

The procedure for deriving the load algorithms thus consisted of the development of the FESDEC finite element model; refinement and verification of the model using the deballast and internal calibration test data; and finally the use of the verified model to obtain the influence matrix for the strain gauges. Unfortunately, the verification and model refinement phase still left uncertainty regarding the accuracy of the derived algorithm.

Due to these uncertainties, Sandwell Swan Wooster Inc., (SSW) was contracted to perform a series of analyses using their comprehensive set of finite element models of the Molikpaq. These models were constructed and used for the original design of the vessel and have since been exercised and refined to perform various studies for Gulf. The work performed by SSW included several different load cases to verify the model. The tests included deballasting of ballast water tank #12 from 21.2 metres to 12 metres, and again down to 6 metres. An actual ice load, recorded on the Molikpaq in 1986, was also run to provide verification of the model's performance during ice loading.

The Swan Wooster study then completed a series of load cases, each consisting of a uniform load, 2 metres deep, applied to the full width of the caisson. These loads provide a measure of the vertical influence curves for the strain gauges and could be extrapolated to obtain load algorithms. One of the load cases representing a 2 metre thick uniform ice sheet was repeated on the model. The magnitude of the load was doubled while all other variables were held constant. In the actual structure, the proportions of load which are ultimately resisted by either base friction or passive response of the sand core may vary with the magnitude of the applied load. This load case was performed to test the effect of changes in these proportions on the linearity of the response of the strain gauges with respect to the magnitude of the applied load.

The major conclusions of the study performed by Sandwell Swan Wooster were:

1. The response of the strain gauges appears to be linearly related to the magnitude of the load applied to the ice face of the caisson. This linearity is not influenced by the ratio of structural resistance afforded to either base friction or to passive resistance of the sand core.

2. The vertical influence curves of the strain gauges within the context of the caisson as a whole, do not appear to be as well behaved as the Arctec model predicted for the bulkhead alone. Thus the applicability of the 3x3 influence matrix to correct for the influence on the response of a particular strain gauge due to load applied to the ice face outside the dimensions of the 'ice load panel', is suspect. This finding also indicates that for ice features of up to 5 metre thickness, the response of the C10 strain gauge alone should provide an excellent measure of the load.

3. The horizontal influence zone for the strain gauges, as established from the internal calibration tests is not correct for instances of large loads applied to the caisson and resisted by the sand core. In this instance, which includes the majority of ice load events, the strain gauges on a particular main bulkhead are influenced by loads applied over a wide section of the ice face. The response of the C10 and C6 gauges on a bulkhead 4.88 metres away from the centroid of the applied load show approximately 50% of the response of the corresponding gauge on the bulkhead immediately behind the applied load. At a distance of 9.76 metres (4 bulkhead spacings) the response is reduced to approximately 10%. The influence zone represented by these results is significantly larger than the horizontal zone of influence indicated by the internal calibration test which shows that for the caisson-only scenario, the gauges are not significantly

influenced by loads applied at more than 2.44 metres from the bulkhead centreline.

In addition to commissioning Sandwell Swan Wooster, Gulf proceeded to explore more empirical means of calibrating and refining the load algorithm. Attempts were made to "fine-tune" the influence matrix derived from the Arctec finite element model to more accurately predict loads. The "fine-tuning" process provided bulkhead-specific matrices which would correct for variations in strain gauge response across a caisson face. Data from the deballast tests were used in this procedure. The Arctec matrix was "fine-tuned" using two slightly different methodologies. The first refinement was accomplished using the ratio of measured strains for a given deballast load against the strains obtained from the multiplication of the original 3x3 Arctec influence matrix and the known deballast loads (Algorithm 4, Table 3.1.). The second method resulted in the FEM-refined 3x3 matrices and used the ratio of measured strain response in the actual structure against the strain values obtained directly from the finite element model subjected to the same deballast load (Algorithm 5, Table 3.1.).

Originally, accurate prediction of loads due to deballasting was believed to be sufficient to verify the accuracy of the ice load algorithm. However, the results of the work performed by Swan Wooster indicated that the behaviour of the caisson during a deballast load is significantly different from that during an ice load event. The variation in behaviour suggests that a load algorithm which accurately predicts deballast loads will likely over-predict loads due to ice.

The changes in hydrostatic pressure acting on the caisson resulting from deballasting are such that there is no eccentricity between the horizontal component of load on the ice face and that on the soil face of the caisson. For every metre of caisson elevation, the horizontal component of deballast load acting on the ice face is exactly balanced by the load on the soil face. This loading geometry results in almost pure axial load in the horizontal struts of the main bulkheads. The bending moment and shear force acting in the horizontal struts is minimal.

Ice-induced loads are applied near mean sea level (15.8 m) over a zone which is approximately equal to the thickness of the ice sheet. The passive soil response is expected to be approximately triangular, varying from zero at the surface of the core and increasing to a maximum at the base of the caisson. The resultant of the soil pressure typically lies at about the 7 metres elevation. The eccentricity between the applied ice load and the passive soil response, produces a large vertical shear component in the horizontal struts of the main bulkheads. This has a significant effect on the strain distribution around the perimeter of the bulkhead cut-outs. The strain distributions for both ice induced loads and deballast test induced loads are illustrated in Figure 3.4 and 3.5.

Comparing Figure 3.4 with Figure 3.5, one can see that, if the magnitude of an ice load (per metre width of caisson face) were the same as the magnitude of a deballast load, the strain response from the C6 strain gauge (or the C10 gauge) would be expected to be significantly greater for the ice load than for the deballast load. Thus, the elements of a [K] influence matrix (units of kN per micro-strain) which accurately predicts deballast loads would be of greater magnitude than the corresponding elements of a [K] matrix for predicting ice loads. In other words, the magnitude of ice loads, as predicted by an algorithm which gives the correct loads for deballasting, should be expected to be over-estimated. Conversely, deballast loads estimated from an algorithm which is accurate for ice loads, are likely under-estimated.

The Arctec matrix, after refinement by the actual:ideal strain ratio, predicts the loads on the ice face due to changes in ballast water level. From the above argument, it would follow that this algorithm would over-estimate ice loads. The FEM-refinement procedure is theoretically more exact than the use of the "actual:ideal" ratio. Loads estimated with the FEM-refined matrices under-predict deballast loads and indicate that the matrix is useful for calculating ice-induced loads. However, without an ice load for which the magnitude is well defined, the accuracy of the FEM-refined matrix in calculating ice loads, cannot be verified.

Correlations of strain gauge response to actual load measured by the Medof panels were also carried out to derive ice load algorithms. In fact a whole series of load algorithms were developed and calibrated using as many independent sources as possible. Initially [2x2] influence matrices were derived from deballast test data for the "C16" and "C6" gauges. These matrices have not been refined.

Three alternate algorithms involved the use of only one strain gauge on each bulkhead. The first is the "C10-Medof Algorithm" (Algorithm 7, Table 3.1). The gauge factor, in units of kNewtons per 4.88 metre width of the caisson per micro-strain response from the C10 gauge, is derived from cross-correlation of Medof panel response with the response from the associated C10 strain gauge. Unfortunately, the low magnitude of the loads involved result in a relatively poor correlation, and therefore, uncertainty as to the accuracy of the gauge factor.

A second C10 gauge factor (Algorithm 6, Table 3.1) was derived from the results of the SSW studies. The vertical influence curve derived from the SSW model indicates that load estimates made using the C10 strain gauge only would be accurate for ice features of up to 5 metres thickness, and its accuracy would be reduced marginally as the ice thickness increased beyond 5 metres. Future work should involve the refinement of the C10 strain gauge factor through the comparison of measured loads and the response of the associated C10 strain gauge.

The final single gauge algorithm (Algorithm 3, Table 3.1) uses only the response from the C16 strain gauges. The gauge factor in this case was derived from the deballast test data. The gauge factor is believed to be conservative, in that it would over-predict the load.

A further 3x3 algorithm used results of the Swan Wooster finite element study (Algorithm 2, Table 3.1). This simplistic derivation was performed to provide comparative calculation of loads using an algorithm derived from a method which is independent of the Arctec finite element analysis. Loads calculated using this algorithm for an actual

ice-structure interaction compared favourably with the loads calculated using the FEM-refined Arctec matrix.

It is believed that the "FEM-refined" Arctec algorithm (Algorithm 5) is the most accurate of those presented for prediction of ice-induced loads. It is therefore recommended that this algorithm be used for research purposes, and that future work should be undertaken to verify the algorithm's accuracy.

The horizontal influence curves, determined from the SSW models raise serious concerns regarding our ability to quantify spatial distribution of local ice pressures using a 3x3 influence matrix. Information obtained from these algorithms regarding spatial distribution of load, or local ice pressures should therefore be treated with caution.

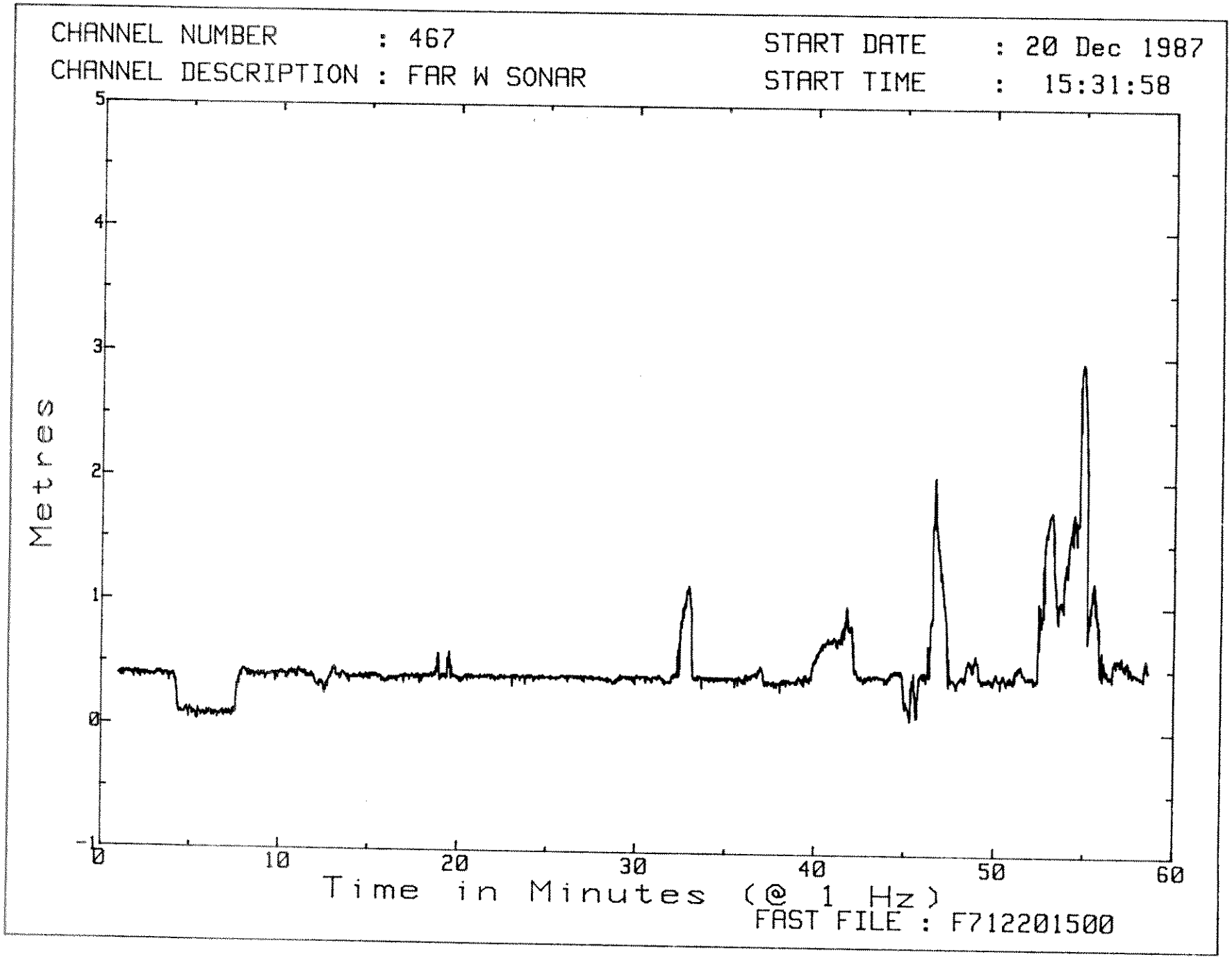


FIGURE 3.3 ICE THICKNESS MEASUREMENT

3.3 Calculation of Ice Loads

The software program 'Macloads' was developed as an in-house Gulf project specifically for this Joint Industry Project. The primary function of the program is to obtain an estimate of local and global ice loads and ice pressures from measured caisson strain gauge responses. Relevant channels of strain gauge data are extracted onto sub-files obtained from the larger data files recorded by the Molikpaq HP200 data acquisition system. Strain gauge responses are converted to equivalent pressure/load estimates using the various stiffness matrices and gauge factors as described in the preceding section.

Four different methods of calculating loads are employed as summarized in the Table 3.2 below. The first two methods obtain a single bulkhead load directly from a single gauge response, while the latter two methods using multiple gauges, divide the bulkhead load into discrete panel loads which are then summed to provide the total bulkhead load. In all methods, caisson face loads are obtained by averaging all of the bulkhead loads along the face then extrapolating this over the full width. Global loads are obtained by geometric summation of the face loads.

TABLE 3.2

CALCULATION OF ICE LOAD

DESCRIPTION OF METHOD	METHOD OF CONVERSION TO LOAD	NUMBER OF BULKHEADS	TOTAL NUMBER OF GAUGES
1. Using C16 gauge response only	'C16' gauge factor	16	16
2. Using C10 gauge response only	'C10' gauge factor	26	26
3. Using combination of C6 and C16 gauges	[2x2] stiffness matrix	8	16
4. Using combination of C16, C10 & C6 gauges	[3x3] stiffness matrix	26	53

Default stiffness matrices and gauge factors for all four methods of calculations are stored internally within the Macloads program. The [3x3] calculation uses a single stiffness matrix as defined in the Arctec calibration report, with seven variations to account for missing or dead gauges. The [2x2] calculation uses matrices derived from several deballasting tests. The C10 and C16 calculations use a single, constant gauge factor for each bulkhead. As described in the preceding section, conversion factors were derived from a series of load algorithms. Emphasis was placed on the [3x3] and single gauge factor, with less use of the [2x2] matrices which were derived solely from the deballast tests.

As required, additional refined [2x2] and [3x3] matrices can be explicitly defined to be used in the calculations. Each defined matrix is numbered sequentially for unique identification and permanently stored. These can then be assigned to the appropriate bulkhead(s) to account for varying bulkhead stiffness within the caisson. Bulkheads that do not have an assigned matrix use a predefined default matrix which is essentially the original Arctec matrix. In a similar fashion non-default gauge factors can be discretely assigned to any bulkhead for use in the C10 and C16 load calculation.

The results of each load calculation are stored onto file for each time step within the file being analyzed, for a total of 192 predefined calculations. Data from both the Extraction file and the Calculation file can be simultaneously accessed for plotting purposes. Time series plots of any channel can be presented with it's associated summary statistics (Min, Max, Median and Variance). Various program features include Auto-scaling, Zoom and Crosshair Annotation. Cross channel plots can also be generated with an optional linear regression best fit applied to the data.

Pressure Distribution plots across the North caisson face can be generated using either the C10 or [3x3] methods of calculation. Calculated pressures at each of the 10 bulkheads are plotted discretely, in addition to averages of adjacent bulkheads taken 2, 5 and 10 at a time. For clarity these distributions are differentiated by line colour and type. They can

either be viewed on the screen in pseudo-real time, animated mode or as single-frame snapshots with the option to request hardcopy raster dump or report quality pen plots.

3.4 Soil Face Strain Gauges

The 10 soil face strain gauges installed on the Molikpaq in August, 1988 are mounted in 5 pairs. Each pair is capable of providing both a soil pressure estimate, as well as the global axial strain experienced by the soil face at the point. The 10 new soil face gauges are in addition to 28 functional soil face gauges originally installed in Japan. The new arrangement allows for calculation of soil pressure at several elevations on both the loaded caisson face and the trailing caisson face. The global axial strain carried in the soil face is a useful indicator of the rate of load dissipation down the sides of the caisson, where the only mechanism of resistance is steel-soil friction.

The algorithms used for the soil face strain gauges are provided in Table 3.3. The locations of the gauges is shown on Figure 3.1.

Although these gauges can not be used to measure ice loads directly, they will lead to an improved ability to determine ice loads for the bulkhead strain gauges. The study performed by Sandwell Swan Wooster as part of this joint industry project, as well as other studies performed for Gulf in the past, have indicated that the stresses in the bulkheads are not particularly sensitive to the stiffness of the soil. For design purposes, the soil pressures were calculated such that as the leading edge of the caisson deforms under the influence of an ice load, the pressure on the soil face increases from the at rest condition. If the deformation is of sufficient magnitude, a full passive soil state is developed. On the trailing edge of the caisson, the soil pressure decreases from the at rest condition, down to the active soil state. The vertical distribution of soil pressure is assumed to vary bilinearly from zero at the free surface of the core, to a maximum at the base of the caisson, with a change in slope occurring at the water level within the core.

Thus, the information which can be provided by the soil face gauges is extremely valuable for refining finite element models of the Molikpaq, as well as improving the overall understanding of the structure's response to ice interaction. In the derivation of ice load algorithms,

modelling suggests that the vertical distribution of the soil pressure may have an impact on the response from the strain gauges - particularly the C6 and C10 gauges. The eccentricity between the vertical centroid of the ice load and that of the soil pressure produces a torsional moment in the caisson. This induces shear flow in the caisson which is evidenced by a significant vertical shear force carried by the horizontal struts of the bulkhead. The SSW study suggests that the C10 and C6 strain gauges respond to this vertical shear.

TABLE 3.3 SOIL FACE STRAIN GAUGE ALGORITHMS

LOCATIONS Intermediate Bulkhead No.	ELEVATION Above Base (m)	SOIL PRESSURE (kPa)	GLOBAL AXIAL STRAIN (micro-strain)
326,80,162,244	18.2	$1.364(\epsilon_f - \epsilon_w)$	$1.327(\epsilon_w - \epsilon_f) + \epsilon_f$
326,80,162,244	7.6	$1.845(\epsilon_f - \epsilon_w)$	$1.258(\epsilon_w - \epsilon_f) + \epsilon_f$
14	18.2	$1.364(\epsilon_f - \epsilon_w)$	$1.327(\epsilon_w - \epsilon_f) + \epsilon_f$
14	7.6	$2.37(\epsilon_f - \epsilon_w)$	$1.05(\epsilon_w - \epsilon_f) + \epsilon_f$
38	18.2	$1.569(\epsilon_f - \epsilon_w)$	$1.194(\epsilon_w - \epsilon_f) + \epsilon_f$
38	7.6	$2.486(\epsilon_f - \epsilon_w)$	$1.085(\epsilon_w - \epsilon_f) + \epsilon_f$
38	1.7	$2.692(\epsilon_f - \epsilon_w)$	$1.071(\epsilon_w - \epsilon_f) + \epsilon_f$
80	1.7	$3.037(\epsilon_f - \epsilon_w)$	$0.973(\epsilon_w - \epsilon_f) + \epsilon_f$

where;
- ϵ_f = *strain measured on stiffener flange* ($\mu\epsilon$)
- ϵ_w = *strain measured on stiffener web* ($\mu\epsilon$)

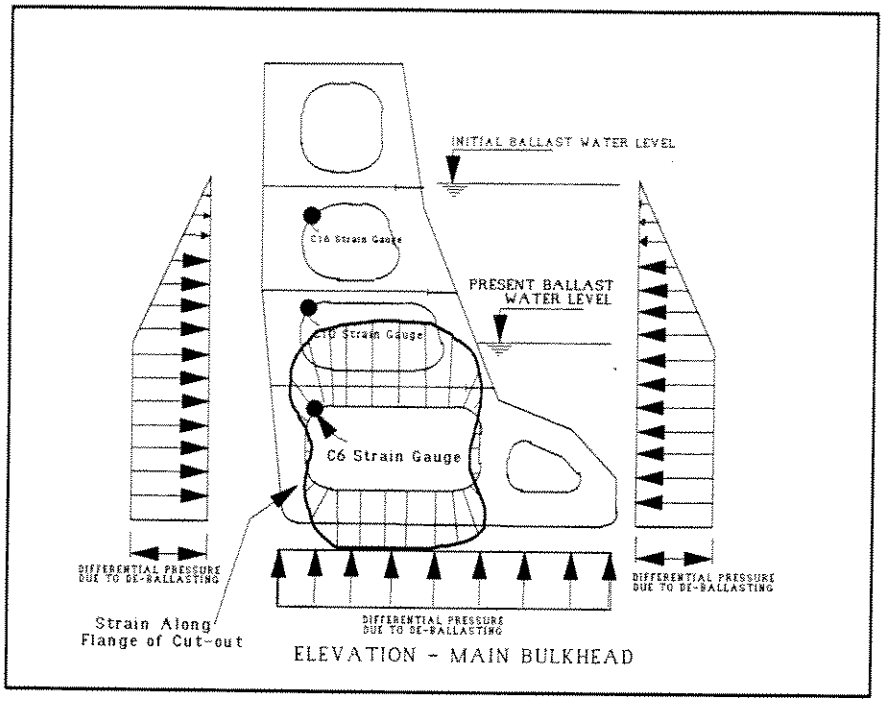


FIGURE 3.4: DE-BALLAST PRESSURE DISTRIBUTION AND STRAIN GRADIENT AROUND C6 CUT-OUT

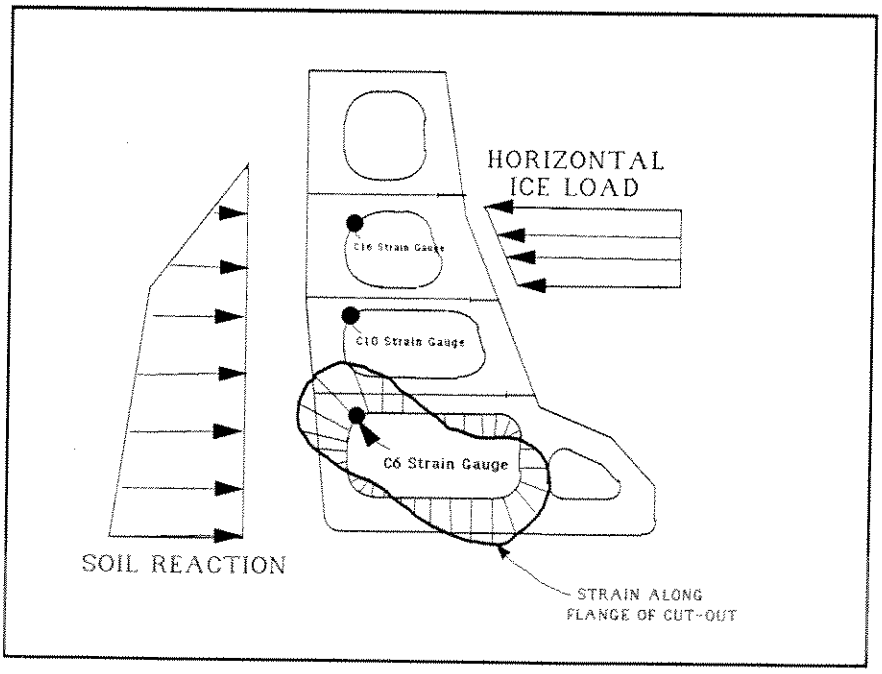


FIGURE 3.5: ICE AND SOIL FACE LOAD DISTRIBUTION AND STRAIN GRADIENT AROUND C6 CUT-OUT

4.0 1987/88 SEASON IN PERSPECTIVE

4.1 Ice and Environmental Conditions

The Amauligak F-24 site is located in the transition zone of the Beaufort Sea ice cover. The transition zone is the active region of ice bounded by the polar pack to the North and by the landfast ice to the south. For most of the winter, the ice in the transition zone is mobile - moving up to 40 n.m. in a day. The interaction between the Molikpaq and the moving ice cover provided an opportunity to collect data about ice-structure interaction.

The ice and other environmental conditions for the 1987/88 season are reported in detail in Phase II, Volume 2 - Operational Records, and Volume 3 - Environmental Conditions. New ice began to form at Amauligak F-24 on October 30. This is slightly later than average, but by no means a record. Growth of the new ice followed the expected ice growth curve through until the end of December, with the maximum ice thickness reaching approximately 1 metre. January experienced a decline in ice thickness from December with the ice being mostly thin first year ice of approximately 0.5m. This changed in February to medium first year, as ice entered the drilling region from the east. Ice thickness in the region again increased parallel to the maximum expected growth curve through February, March and April though actual thicknesses were less. The maximum ice thicknesses reported from the Molikpaq were 1.8 metres through much of April. The far west sonar unit provided quantitative readings of ice thickness until late February 1988. All other data was inferred from visual observations.

On March 1st, a large first year floe became lodged between the Molikpaq and the landfast ice to the south. This floe, which linked the rig to landfast ice, remained relatively stationary through to April 26th. The area immediately north of the rig was open water which gradually froze and by April 10th, was covered with 50 to 70cm, thin first year ice. A general northwesterly movement of the polar pack in mid April resulted in movement of the new ice north of the rig on April 17th and an E-W lead developed which extended from east of the site through to Herschel Island

with the Molikpaq situated on its southern edge. This lead continued to widen during break-up so that the Molikpaq experienced no loads due to interaction with ice in the transition zone to the north of the lead. In addition, the increased open water fetch afforded by the lead allowed a significant swell to develop following moderate to strong NNE winds in late April. The swell caused the ice to the south of the site to break up into small (10 to 30m diameter) blocks which then floated away without inducing loads on the structure. Much of the landfast ice was also subject to the same fate.

The magnitude of ice loads experienced by the Molikpaq is predominantly a function of the ice thickness and velocity. Of particular interest are interactions with thick multi-year ice features. These features are prevalent along the southern edge of the polar pack. During the winter of 1987-88, the Polar Pack remained far to the north of the site (see Figure 4.1) and the Molikpaq was not exposed to any multi-year ice features. Although this was particularly well received by the drilling personnel, it was less than ideal for a research program.

The loads experienced at Amauligak F-24 were far below those of either the Tarsiut P-45, 1984-85 deployment (20,000+ tonnes) or the Amauligak I-65, 1985-86 deployment (50,000+ tonnes). The maximum global load reported from the Molikpaq during 1987-88 was only 7,800 tonnes on 5 Jan '88 (see Figure 4.2). This interaction was due to 0.8 metre ice drifting at approximately 0.3 knots toward 120° True - resulting in loading of the N, W and NW caisson faces. The interaction however, was not of sufficient magnitude to trigger either a fast or a burst file. In fact, during the entire drilling season, not one interaction produced sufficient response to automatically trigger an increase in scan rate of the data acquisition system.

Details of the loading experienced at Amauligak F-24 are presented in Phase II, Volume 5 - Ice Loads and Pressures, Ice Structure Interaction. Generally, the low levels of loading experienced by the Molikpaq may be attributed to three major factors:

1. Ice conditions at Amauligak F-24 were very mild, with the multi-year ice remaining far to the north of the drilling site during the entire season.
2. Early in the season, a large grounded rubble field developed around the Molikpaq and effectively insulating the Molikpaq from ice loads for much of the year.

3. The predominant mode of failure of ice against the caisson was flexure, as opposed to crushing for previous deployments. The change in set down draft from 19.5 metres to 15.8 metres resulted in virtually all ice interactions occurring against a caisson face sloped at 23° from vertical rather than 6.7° for the section of the caisson above 16.4 metres elevation. The change in face angle had a significant effect on the failure mode of the first-year ice and apparently on the global ice loads as well.

The predominance of the flexural mode of failure contributed to the development of grounded rubble. The block sizes resulting from flexure are much larger than those resulting from crushing. The increased block sizes coupled with the decreased set-down depth resulted in a reduced clearing capacity around the Molikpaq and eventually to the accumulation of rubble.

The change in predominant failure mode from crushing to flexure appears to have contributed to a reduction in ice loads. Although load estimates from the strain gauges are not believed to be highly accurate for low levels of loading, all load estimates (as well as structural response characteristics) indicate that, for similar ice conditions, loads experienced at Amauligak F-24 were well below those experienced at either of the two previous deployments of the Molikpaq.

Dynamic, cyclical ice loads were not recorded during the '87-'88 season. However, the same phenomenon which produced cyclic, dynamic ice loads on the Molikpaq in previous years was observed at Amauligak F-24 in December. The interaction was the result of a long narrow (approx. 10m

width) wedge of ice trapped between two large first year floes. The ice was thin first year of 50 to 60 cm thickness. The cyclic-dynamic interaction lasted only a few seconds, and resulted in no discernible dynamic loading on the structure.

4.2 Rubble Studies

A large, grounded rubble pile developed at Amauligak F-24, starting on December 20, 1987 on the east and NE caisson faces. The rubble pile remained until May 1988.

The development of the rubble pile was initiated with failure taking place against the caisson until sufficient bulk of rubble was created. The ice failure then shifted to the perimeter of the rubble. Provided the drift direction remained relatively constant, the rubble pile continued to develop, with the incoming ice sheet repeatedly riding up on the floating rubble to fail in flexure, or crushing against the outer edge. Finally, the rubble pile grounded-out at which time, a sharp reduction in load on the caisson could be noted. By the end of January, the Molikpaq was completely surrounded by grounded rubble.

Supplementary studies to the Joint Industry Project were initiated in January and February 1988 to allow documentation of the rubble pile, and monitor any load transfer during ice interactions. The supplementary studies were comprised of separate projects as follows:

- The CRREL Studies

  CRREL's objective was to deploy 12 ice stress sensors in the rubble field to measure ice force transmission through the rubble. Each sensor was connected via an instrumentation cable to a Campbell Scientific CR10 data logger. All 12 data loggers were placed outdoors on the East side of the caisson main deck behind the ice deflector.

The CR10s were connected to a Hewlett-Packard 310 computer using coaxial cables. The HP 310 computer interrogated each CR10, and transferred the data to a Bering Bernoulli disc drive. The hard disc was capable of compiling 81 hours of data at a sampling rate of 0.2 Hz.

o The NRC Studies

NRC's objective was also to measure the transfer of ice forces through the rubble pile. In addition, attention was given to characterizing the rubble field, i.e. survey of the rubble, determining the thickness of the consolidated layer and monitoring of horizontal and vertical movements.

The components of the measuring system included four small ice pressure sensors which were connected to a CR10 data logger located on the rubble. Power was drawn from a 12V lead-acid battery. The data logger was connected via an instrumentation cable to an IBM PC which was located within the box girder deck of the Molikpaq. The scanning rate was once every 15 seconds. Two IDEAL panels were placed in the consolidated layer of the rubble pile. Data from these panels were acquired with the aid of a Terra 8 data logger which was placed on the ice close to the panels. The scanning rate was once every 30 minutes.

Two "consolidation gauges" were placed at various depths in order to monitor possible consolidations of the rubble. Wild-reflectors were mounted on eight survey posts which in turn were located on the rubble. A transit in connection with an EDM was placed on top of the ice deflector for monitoring displacements of the rubble. The rubble was surveyed every two weeks.

- The CCTV System

  The objective of the video system was to document failure mechanisms between impacting, floating ice and the rubble pile as well as to monitor visible changes and displacements of the rubble. This was achieved by placing low-light cameras not only at the caisson edge but also by mounting two cameras on specially designed booms directly over the outer edge of the rubble. A total of seven cameras were utilized (two on the derrick, three on the ice deflector and two on the rubble pile) for ice/rubble interaction documentation. The locations of the cameras and the CRREL sensors are shown on Figure 4.3.

The use of the CRREL thermo drill for installing and retrieving sensors in the rubble proved to be very effective. The overall performance of the sensors was satisfactory. A few sensors and video cameras malfunctioned for short periods due to operational interferences. With regard to data gathering, all three systems (NRC, CRREL - and video system) performed well. Unfortunately, no impact data was collected due to the lack of ice movement in the rig vicinity. Field work for the supplementary studies was terminated in late April/May 1988.

The characteristics of the rubble pile were profiled along 3 lines using 2" auger holes. From these lines, the average consolidation thickness and depth of the consolidated layer below water level amounted to 4.45 m and 3.52 m, respectively. Most of the lower level areas of the rubble pile were floating. It is of interest to note that the outer rubble pile with its high sails was only partially grounded. A schematic section through the rubble pile is shown in Figure 4.4

In parallel with the rubble studies described above, Challenger Surveys & Services Ltd., was contracted to develop a system to track ice movement around the Molikpaq. The requirement was to track velocities and drift directions of the ice up to 1000 metres from the Molikpaq. This information would then be combined with data collected by the Data

Acquisition system and used in the ongoing study of ice loading on the structure.

System development began in February and was completed prior to departure to the field on April 5, 1988. Hardware/Software deployment and installation on the Molikpaq happened between the 5th and 9th of April. Testing of the system and training of the ice observers in its operation took place on April 10th and 11th. Deployment of the Electronic Distance Measurement reflectors at various locations off the north and east faces of the Molikpaq was performed with helicopter support.

No movement of the reflectors was observed during the first week of the program. Once the ice started to move it was found that it moved so rapidly (.5 knots) that it was difficult to track the reflectors with the theodolite.

Additional deployments took place as the existing reflectors moved out of range. To increase the observation range and make it easier to track the reflectors, the small 2.5 inch diameter reflector were replaced with 6 inch ones. The observation program was continued until early June.

Descriptions of these supplementary studies can be found in Volume 6 of the Phase II report. NRC and CRREL are also preparing separate reports outside the scope of this Joint Industry Project to document results from stress sensor measurements. These reports can be requested directly from the following addresses:

Department of the Army
Cold Regions Research and Engineering Laboratory
Corps of Engineers
Hanover, New Hampshire 03755-1290

National Research Council
Division of Building Research
Montreal Road Laboratory
Ottawa, Ontario K1A OR6

FIGURE 4.1: DISTANCE FROM HAZARDOUS ICE

Molikpaq @ Amauligak F-24, 1987-88

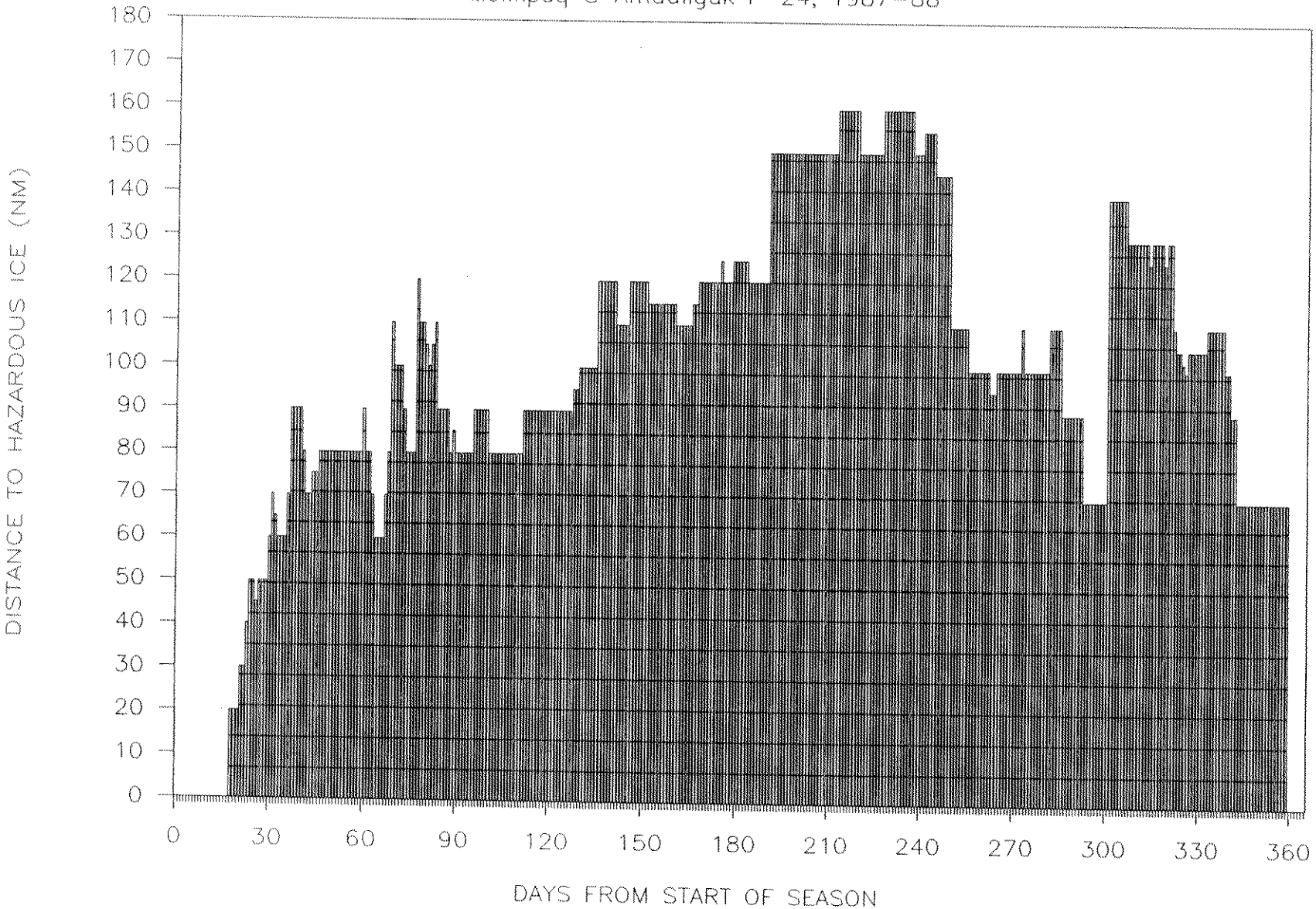
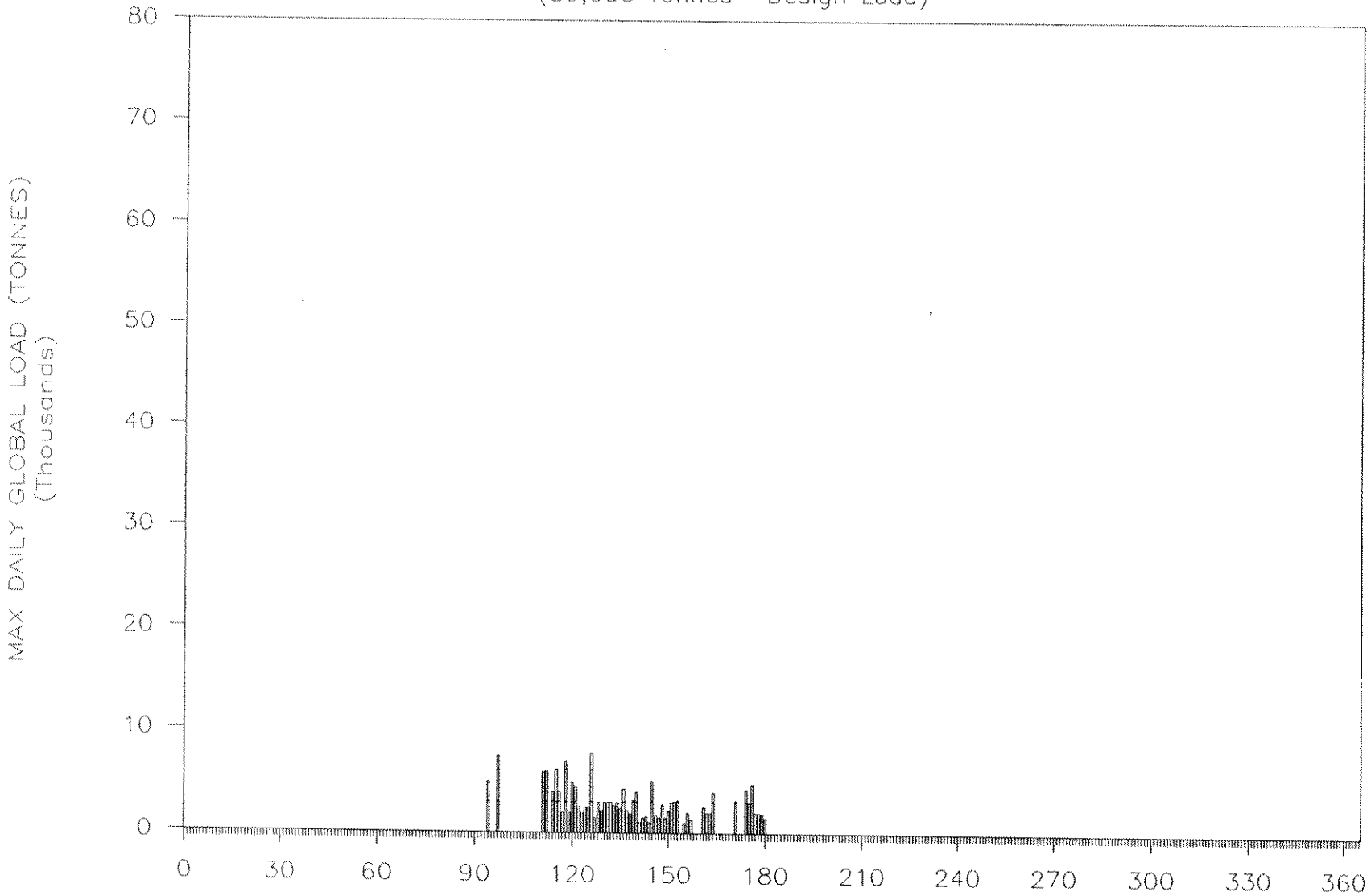
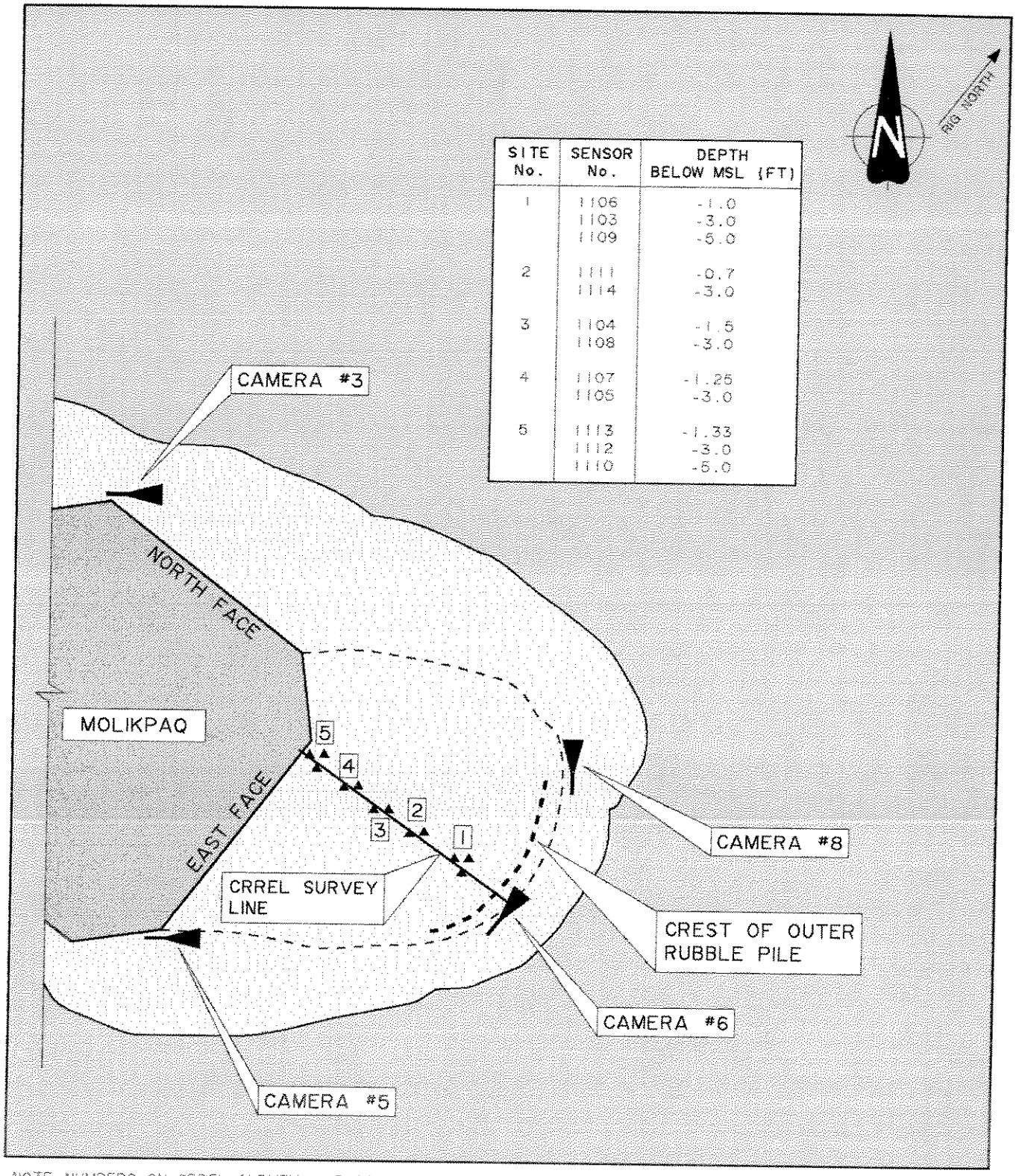


FIG 4.2: MAX DAILY GLOBAL LOAD, 1987–88

(80,000 Tonnes= Design Load)





SITE No.	SENSOR No.	DEPTH BELOW MSL (FT)
1	1106	-1.0
	1103	-3.0
	1109	-5.0
2	1111	-0.7
	1114	-3.0
3	1104	-1.5
	1108	-3.0
4	1107	-1.25
	1105	-3.0
5	1113	-1.33
	1112	-3.0
	1110	-5.0

NOTE: NUMBERS ON CRREL SURVEY LINE INDICATE THE SITE NUMBER.

FIGURE 4.3

LOCATION OF CRREL SENSORS AND VIDEO CAMERAS IN RUBBLE PILE AS OF MARCH 13

FILE NO. ENG:[183,53]DIA014.;1 88/04/21 VRD

88F004

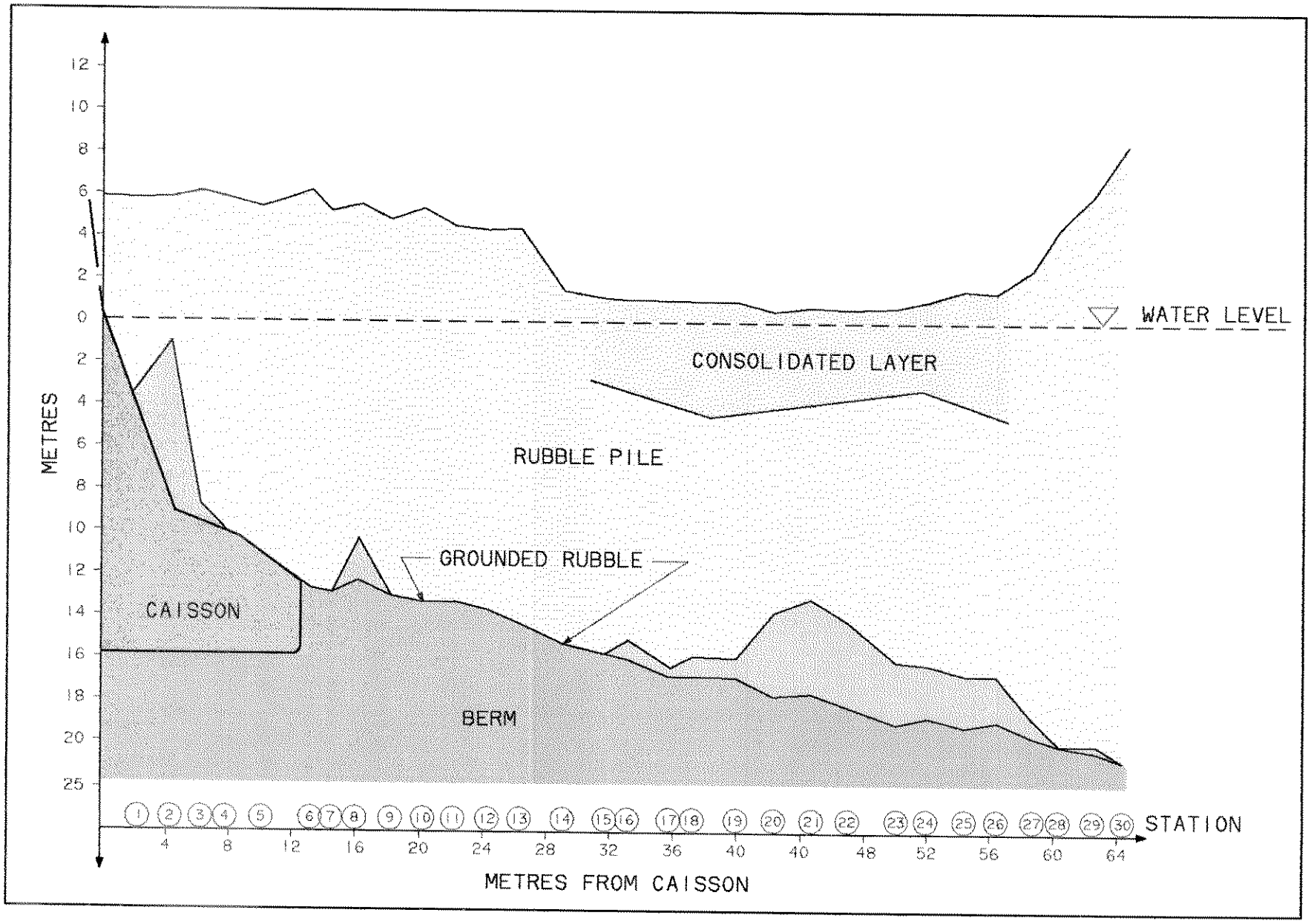


FIGURE 4.4

CROSS-SECTION THROUGH RUBBLE PILE BETWEEN HOLE #1 AND #30

FILE NO. ENG:0163,53)DIA025L,1 88/07/20 VRD

86F004

5.0 CONCLUSIONS

5.1 Global Ice Loads and Pressures

During the 1987-88 season, the Molikpaq did not experience a single ice-structure interaction resulting in more than 10,000 tonnes global ice load. The maximum global load (from field estimates) was 7,800 tonnes from 330° rig-north. This load occurred on January 5, 1988 and resulted from interaction with 0.8 metre thick first-year ice travelling at a drift speed of 0.3 knots and drift direction of 120°T. Caisson face loads were calculated as 6000 tonnes on the north face, 3300 tonnes on the west face and 1000 tonnes on the northwest face. For this level of loading, no accurate pressure measurements can be deduced.

Ice loads and pressures experienced by the Molikpaq were below expected values as compared to data for similar ice conditions from previous deployments. This is attributed to two major factors;

i) The change in face angle from 6.7 to 23 degrees from vertical appears to have resulted in more flexural failure of the thin first-year ice; and

ii) The formation of the rubble pile had a significant load mitigating effect for interactions involving the thin ice features.

Unfortunately, it is not possible to extrapolate from the narrow range of ice thicknesses experienced this year to predict the load mitigating effect of the change in face angle and the rubble pile for thick multi-year ice features. Multi-year ice features remained between 70 to 150 nautical miles from the Molikpaq during the entire season.

The Molikpaq deployment at Amauligak F-24 did show that it is possible for a stable rubble pile to develop in 14 metres of water, without the aid of rubble generators or spraying techniques. The rubble pile began forming off the north/northeast face in late December. By late January a

considerable mound had developed on the north, west and east faces. The cover photograph for this report indicates the extent of the rubble pile. Very little change was then noted in the extent of the rubble until break-up started on April 26, 1988.

5.2 Future Instrumentation

A significant conclusion of this study is that it will be necessary to compare the loads estimated by the ice load algorithm with the actual loads as measured by an independent method to validate accuracy. This is presently only possible on the Molikpaq to a very limited extent at a 15.8 m setdown through the use of the two functional Medof panels. Unfortunately, these panels do not sample a sufficient areal extent to provide a good correlation. It is therefore recommended that physical calibration of the strain gauges should be the focus of attention for future studies. Additional finite element analyses are not recommended until the existing strain gauge load algorithms have been thoroughly evaluated by comparison with other load measurements.

To complete this evaluation, new externally mounted ice load panels should be installed on the Molikpaq. The new panels should allow dynamic load measurement, and cover a minimum 10-15% of the north face. These panels would provide a means of verifying the accuracy of the strain gauge load algorithms. Once calibrated in this manner, the gauges should provide a reliable means of measuring global and local ice loads on the Molikpaq.

Similarly it is recommended that load/pressure panels should be installed at the sand core/caisson interface to confirm the algorithms developed for the sand face strain gauges. These panels should incorporate pore water pressure measurements, as well as readings of total pressure.

With these proposed upgradings to the present instrumentation, the Molikpaq will be well suited in future deployments to provide further research measurements of ice-structure interaction in the transition zone of the Beaufort Sea.