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RÉSUMÉ

Les forces agissantes des banquises désignent les forces limitatives qui peuvent s'exercer dans celles-ci. La compréhension de ce phénomène est importante pour :

- la détermination des charges de glace s'exerçant sur les structures (la méthode des forces agissantes limitatives);
- la modélisation et la prévision du mouvement des glaces;
- la fixation de l'itinéraire des navires dans l'Arctique.

Jusqu'à récemment, on avait spéculé sur les forces limitatives des banquises mais sans jamais les mesurer. Ce document décrit une expérience pilote visant à déterminer des valeurs types des forces agissantes des banquises sur une distance de plusieurs kilomètres, dans la partie sud de la mer de Beaufort.

Des capteurs de poussée des glaces in situ ont été installés près du milieu d'un floe pluriannuel. Le floe était soumis à des conditions de glaces convergentes et un encrêtement s'est produit autour de lui. On a mesuré les contraintes de compression correspondantes qui s'exerçaient dans le floe, puis on en a déduit les forces de banquises moyennes liées à l'encrêtement observé.

Le docum[...] iel utilisé et les résultats ol[...]

A PILOT EXPERIMENT TO MEASURE ARCTIC PACK-ICE DRIVING FORCES

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Abstract

Pack-ice driving forces are synonymous with the limiting forces that can be transmitted through pack ice. Knowledge of this topic is important in relation to:

- ice loads on structures (the limiting driving force approach)
- ice motion modelling and forecasting
- arctic ship routing

Until recently, limiting pack-ice forces had been speculated upon but never measured. This paper describes a pilot experiment to measure typical values for pack-ice driving forces across a width of several kilometres in the southern Beaufort Sea.

In-situ ice pressure sensors were installed near the middle of a multi-year floe. The floe was subject to converging ice conditions and pressure ridging occurred around it. Corresponding compressive ice stresses in the floe were measured from which the average pack-ice forces associated with the observed ridging could be inferred.

The paper describes the background to the project, the general approach, the equipment used, and the results obtained.

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Introduction

The maximum sustainable internal stresses within pack ice are synonymous with the driving forces which pack ice can exert on large ice features embedded within it; hence the term pack-ice driving forces. Pack-ice driving forces are of interest with respect to arctic operations for several reasons. First, under certain circumstances, ice loads on structures are influenced by pack-ice driving forces. Second, ice motion forecast models require realistic input of internal pack-ice strength. Third, techniques for predicting areas of pressured pack ice are important in arctic ship operations.

In terms of ice force models, the limit-force condition (Croasdale 1980, 1984) is governed by pack-ice driving forces. This is illustrated conceptually in Figure 1. A thick ice feature (e.g. multi-year floe or ice island) is being forced against a structure by moving pack ice. Once the ice feature is at rest, the integrated driving force is made up of the pack-ice driving force, the wind drag and, if applicable, the current drag. If this total force is less than that required to locally fail the thick ice at the structure, then it will be the limit-force load which will govern.

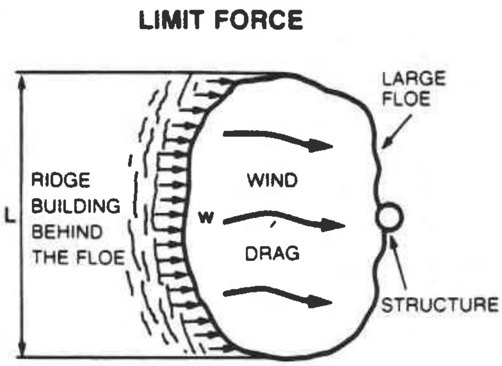

FIGURE 1: LIMIT-FORCE ICE LOAD GOVERNED BY DRIVING FORCES (F = wL + WIND DRAG)

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It is suggested that the pack-ice driving force across the floe width is governed by the failure of the pack ice across the width of the lodged floe. The process of large-scale ice failure within pack ice has been discussed by several investigators (e.g. Hibler 1980; Rothrock 1975; Parmerter & Coon 1973). It has been pointed out that within pack ice, the most common form of ice deformation and ice failure is pressure ridging. Furthermore, observations of pressure ridges indicate that over much of their length, the failure process appears to be one of flexural failure rather than ice crushing.

Previous investigators have speculated on the forces necessary to create pressure ridges. Reviews of previous work on estimating pressure ridge building forces have been conducted by Vivitrat and Kreider (1981), Croasdale (1980, 1984) and others (e.g. Michel 1983). Also, model testing has been used as an approach to better quantifying ridge-building forces (e.g. Abdelnour & Croasdale 1986). Typical values for estimates of ridge-building forces and their sources are given in Table 1. The range of values is at least one order of magnitude. The lowest values are those associated with geophysical scale ice motion predictions, and averaged forces obtained from energy approaches. The highest values are those obtained considering ice failure across a narrow width. Given the fact that ridge building across a wide front will probably not be simultaneous, then both the high values (across a narrow width) and the low values (averaged over several km) are not necessarily incompatible.

The other point of significance is that in Table 1 no data exists which is based on full-scale measurements. It was this lack of real data which provided the rationale and incentive for this project. The objectives of the project were to assess how measurements of average pack-ice forces could be accomplished, and to conduct a field pilot experiment. (See Croasdale and others 1986, for the full project description and detailed results).

Overall Approach

Recognizing that it is the spatially averaged ridge-building or pack-ice forces across a wide front that are of interest, the general concept for measuring them was to measure internal ice stress at the centre of a multi-year floe in an area of converging pack ice; this is shown conceptually as Figure 2. This approach uses the instrumented multi-year floe as a large transducer which senses the average pack-ice forces applied to it.

It was recognized at the outset, that the success of this approach depended on:

- o An ability to reliably measure low ice stresses.
- o An ability to interpret the internal stresses near the centre of the floe in terms of pack-ice forces at the perimeter.

Table 1
Estimates of ridge-building forces (various sources)

Source	Approach	Range of Values for Ridge-building Force (Nm^{-1})
Parmerter & Coon	Ridge-building math model	1.0 to 3.0×10^4
Hibler	Large-scale ice motion modelling	10^4 to 10^5
Rothrock	As above	0.4 to 1.0×10^5
Mellor	Math model for ridge building (2 m ice)	5×10^4
Nevel	Math model for ridge building (1 m ice)	0.4 to 1.0×10^5
Vivitrat & Kreider	Review of rubble bldg. & Ridge building models	1.5 to 7.0×10^5
Abdelnour & Croasdale	Narrow width model tests	up to 5.0×10^5
Croasdale	2-D theory for fracture & ride-up (1 to 2m ice)	0.35 to 1.1×10^5

o Confidence or knowledge that the measurements either represented a limit to the pack-ice forces, or could be correlated with pressure ridging around the floe.

During this project, each of the above issues was addressed. The first issue was addressed by developing and testing, in a cold room, newly designed ice stress sensors suitable for measuring relatively low ice stresses. The second issue was addressed partly by mathematical modelling and partly by examining the results from the field. The third issue was addressed in this experiment by correlating ice stress events with floe motion, and actual observations of pressure ridging around the floe.

This paper concentrates on the field experiment and discussion of the results. First, however, a brief overview of the design of the sensors and also the cold room tests is provided.

The Ice Stress Sensors & Cold Room Tests

Measuring stresses within an ice feature is not simple, mainly because the deformation behaviour of ice under stress is not simple. Ice is a material close to its melting point. Its deformation characteristics are therefore strain-rate dependent and they also vary with temperature. This is the main reason why one cannot simply measure the strain in the ice and convert it to stress using an elastic modulus, as one would with linear elastic materials such as metals. Nevertheless, despite these difficulties, the theory of inclusions has been successfully used to develop an interpretation procedure for sensors inserted in an ice sheet (Metge and others 1975).

Based on previous work by the authors and others, the technology of in-situ ice stress sensors is fairly well understood. At the same time,

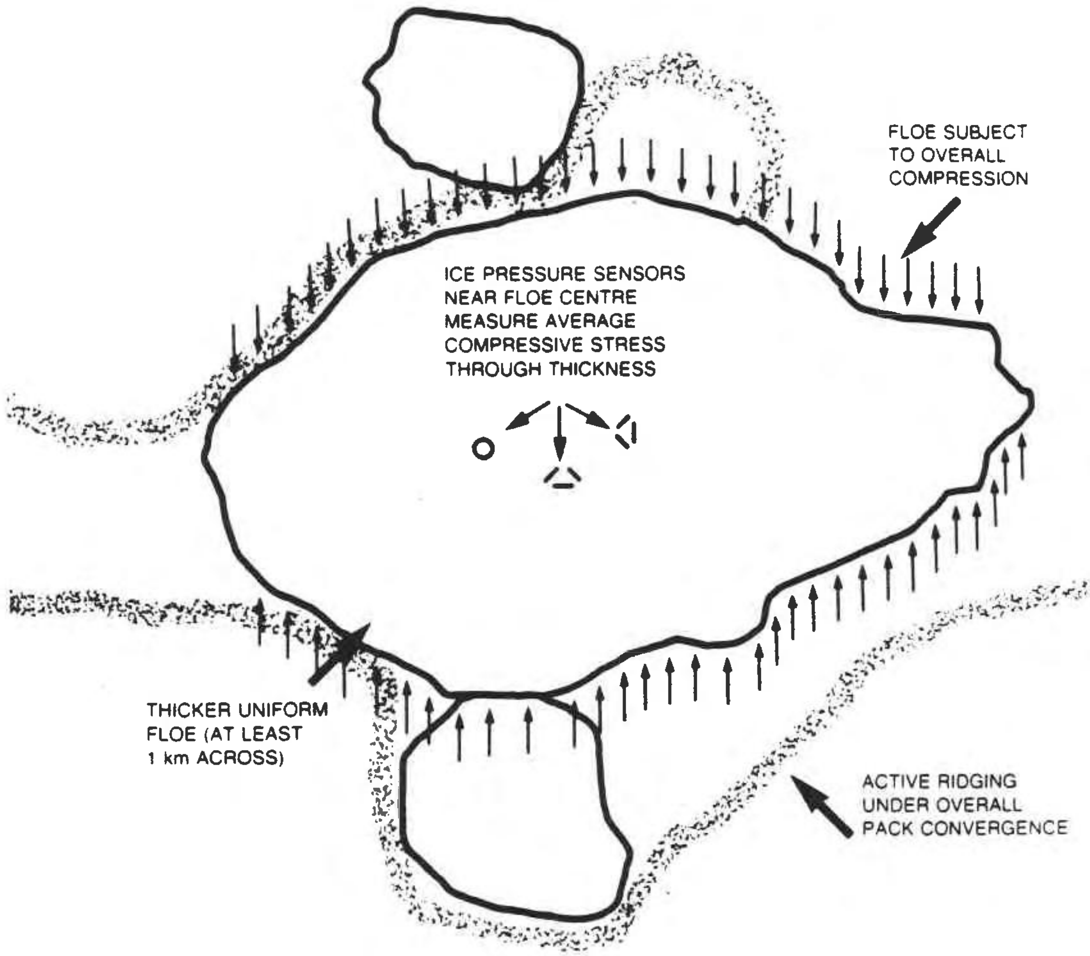

FIGURE 2: OVERALL SCHEME FOR MEASURING PACK-ICE FORCES

however, it was recognized that previous use of ice pressure sensors had been different from in this project. They had been used mostly in the range of ice pressure expected locally in front of fixed structures, e.g., 0 to 3500 kPa. Whereas, for this project, sensors with a working range of about 0 to 100 kPa were required. (Table 2 indicates the relationship between the average ridge-building force (w) and the average stress at the centre of a 5 m thick floe, assuming uniform compressive stress.)

Table 2

Relationship between average floe compressive stress (σ_c) and ridge-building force (w) for a floe thickness of 5 m

w	Nm^{-1}	10^6	3.5×10^5	10^5	2×10^4
σ_c	kPa	200	70	20	4

The issue of measuring in a reliable, unambiguous way these low stress levels could not be taken lightly (despite the favourable previous experience with stress sensors). Potential problem areas were considered to be:

- o Configuring the sensor to have high sensitivity yet maintaining a constant and known inclusion factor regardless of the effective ice modulus.
- o The effects of long-term zero drift.
- o The effects of temperature changes.
- o The effects of freeze-in stresses and their dissipation.
- o Installation and operational procedures in relation to the above issues.

These problems were addressed in the first part of this project which involved the design of the ice stress sensors and their testing in a cold room. In the sensor design phase it was concluded that existing sensor technology could be adapted to measure low ice stresses. Based on previous work by the authors (Croasdale and others 1986) it was felt that internal strain-gauged elements, as used in typical panel sensors, could be used singly (or in an array of three) in a sensor which would be about 1.0 to 1.5 cm thick and up to about 40 cm in diameter. It was calculated that a resolution of about 1 kPa was achievable with an inclusion factor close to 0.9. Sensors based on this configuration were built for cold room testing.

The other type of sensor built for this project was based on a small hydraulic flatjack (or total pressure cell) connected to a pressure transducer with a suitable range. The major concerns with this type of sensor were complete elimination of air from the hydraulic fluid and the effects of thermal expansion. Successful use of these types of sensors by others suggested these problems could be overcome. In any case, it was intended to monitor temperature of the sensors in the ice, anticipating that any obvious changes of calibration with temperature could be corrected.

Testing of the sensors involved calibration in a press and also within loaded ice blocks. Both sensors exhibited very consistent and linear response when tested in a press.

Results obtained from testing the sensors in loaded ice blocks were not as good, there being some non-linearity and apparent hysteresis. It was not clear whether these effects were real sensor characteristics, or due to other causes, e.g. stress-redistribution in the loaded ice blocks with time. In any case, it was judged that the sensors had a good enough performance for this pilot experiment, although further sensor testing and development would have been desirable (and should be done before more comprehensive field measurements are implemented).

The Field Deployment

The field program commenced on April 11, 1986 and was completed by May 5, 1986. The general location was the Canadian Beaufort Sea about 40 km offshore in about 30 m of water. This was close to the Gulf Canada Resources caisson drilling structure (the Molikpaq). Prior to going to the field, synthetic aperture radar imagery of the ice in the vicinity of the Molikpaq was inspected. Several multi-year floes were identified as potential candidates for the experiment. On one of these floes, which was about 16 km east of the Molikpaq, Gulf had placed a satellite-reporting ARGOS buoy. This floe was inspected during a field visit and was selected as the floe for the experiment. It appeared to be of relatively uniform thickness, was a good size (about 4.5 x 2.5 km), and had the advantage of the ARGOS buoy, by which daily positions could be obtained. On the first visit to the floe, a radio beacon was installed in order to assist in finding the floe on subsequent visits. For redundancy, a second radio beacon was installed a day later. With the ARGOS buoy, and the radio beacons, no difficulty was experienced finding the floe during the course of the experiment, despite the fact that the floe drifted a total of about 100 km.

Approximate floe shape and dimensions were obtained by scaling off the SAR imagery, these are shown in Figure 3.

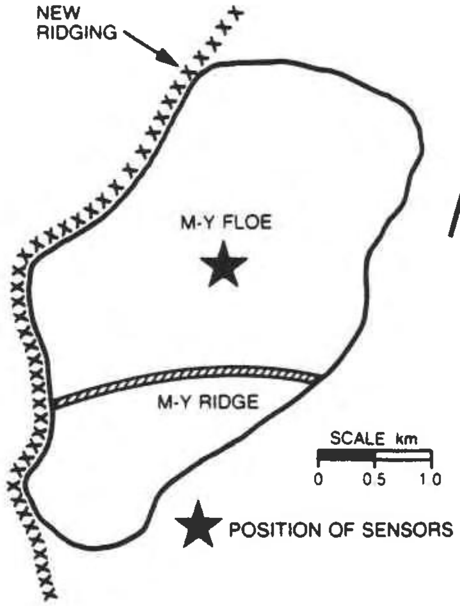

FIGURE 3: FLOE SIZE AND SHAPE

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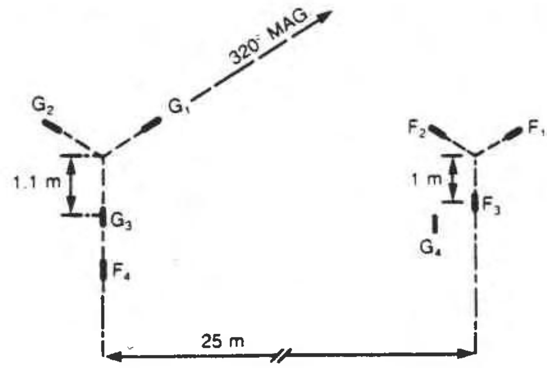
The site location on the floe was selected to be approximately in the middle of the floe width. The site was selected on the basis of being relatively flat and, as best as could be judged, free from major cracks (although a snow cover of between 0 and about 10 cm inhibited our ability to judge the quality of the ice). The ice thickness in the vicinity was measured to be in the range of 1.7 m to 3 m.

Two groups of four sensors were installed within 25 m of each other. Table 3 describes each sensor group. The ice stress-meters were deployed in a "star" rosette pattern at each location as shown in Figure 4. These rosettes were arranged such that the arms of the rosette were all comprised of the same type of ice stress-meter. A redundant stress-meter of the alternate type was placed in parallel with one of the rosette arms to allow direct comparison between the two sensor types. Sensors in each rosette were placed a minimum 1 m apart. Thermistors were used to monitor the temperature of the sensors in the ice (at the sensor depths) and the air temperature.



F120 819 FIGURE 4: SITE LAYOUT

Prior to installing the sensors in the ice, they were again checked to be functioning (by standing on them) and zero's were set. Data recording commenced as soon as they were flooded.

Photographs of sensor installation and the general site layout are shown in Figure 5.

The sensors designated Group 2 were installed first (on April 13, 1986). This took about 8 hours. The sensors were installed in dry slots, prepared using an auger, chain saw and ice chisel. They were frozen into the ice by initially covering the sensors with freshwater which was transported from Tuktoyaktuk. One day later, when this water had frozen, holes were drilled in the sensor slots which allowed seawater to flood the remainder of the slots. Sensors were placed in the depth range of one half to one third the ice thickness from the surface. This put them at about the 1 m depth.

On April 14, 1986, the sensors designated Group 1 were installed using similar techniques, except that sea water was used to flood the slots rather than fresh water (because of the logistical difficulties of bringing enough fresh water to the site). It was judged that the ice temperature was

FIGURE 5: GENERAL VIEW OF THE SITE AND SENSOR INSTALLATION

sufficiently low that the difference in ice modulus between fresh and saline ice would not affect the sensor readings.

Removal of the sensors was accomplished using a hot water generator on May 1 (Group 2) and May 3 (Group 1). Zero readings were taken for all sensors.

Field data was logged on-site and retrieved by physically accessing the ice floe. Raw time series data was recorded continuously during the field monitoring period. Air and sensor temperatures were recorded at hourly intervals along with the date and time (i.e., hour and minute) at which these measurements were made. Ice stress-meter data was initially recorded at a fifteen second per channel scan rate. Subsequently, the scan rate was reduced to 60 seconds per channel to allow a greater time period between site visits.

Stress Measurement Results

During the days following installation, the sensors appeared to respond to freeze-in stresses and temperature transients. Most sensors exhibited cyclic outputs which could be correlated with the daily variations in air temperature and no "real" stress events appeared to occur. During this time, the floe was in a diverging ice field, as offshore winds opened leads between the pack ice and the fast ice; the floe being carried along by the general motion of the pack ice, see Figure 6.

After about April 18, none of the sensors exhibited any cyclic output that could be linked with varying air temperature. This could have been due to the drifting snow re-establishing the snow cover, which was in the range of 20-30 cm in the sensor area.

Table 3

Sensor Installation Summary

Sensor Group No.	Sensor Designation	Parameter Measured	Sensor Type	Sensor Manufacturer & Model No.
1	Gauge #1	Ice Stress	Strain-gauged metal buttons	Arctec Canada Ltd. ACL1
	Gauge #2	Ice Stress	Strain-gauged metal buttons	Arctec Canada Ltd. ACL2
	Gauge #3	Ice Stress	Strain-gauged metal buttons	Arctec Canada Ltd. ACL3
	Flatjack #4	Ice Stress	Flatjack	Geotechnical Res. Ltd.
	Thermistor #1	Gauge #1 Temp.	Thermistor	Campbell Scientific Ltd. Type 107B
	Thermistor #2	Gauge #2 Temp.	Thermistor	Type 107B
	Thermistor #3	Air Temperature	Thermistor	Type 107B
	Thermistor #4	Flatjack #4 Temp.	Thermistor	Type 107B
2	Flatjack #1	Ice Stress	Flatjack	Geotechnical Res. Ltd.
	Flatjack #2	Ice Stress	Flatjack	Geotechnical Res. Ltd.
	Flatjack #3	Ice Stress	Flatjack	Geotechnical Res. Ltd.
	Gauge #4	Ice Stress	Strain-gauged metal buttons	Arctec Canada Ltd. ACL4
	Thermistor #1	Flatjack #2 Temp.	Thermistor	Campbell Scientific Ltd. Type 107B
	Thermistor #2	Flatjack #1 Temp.	Thermistor	Type 107B

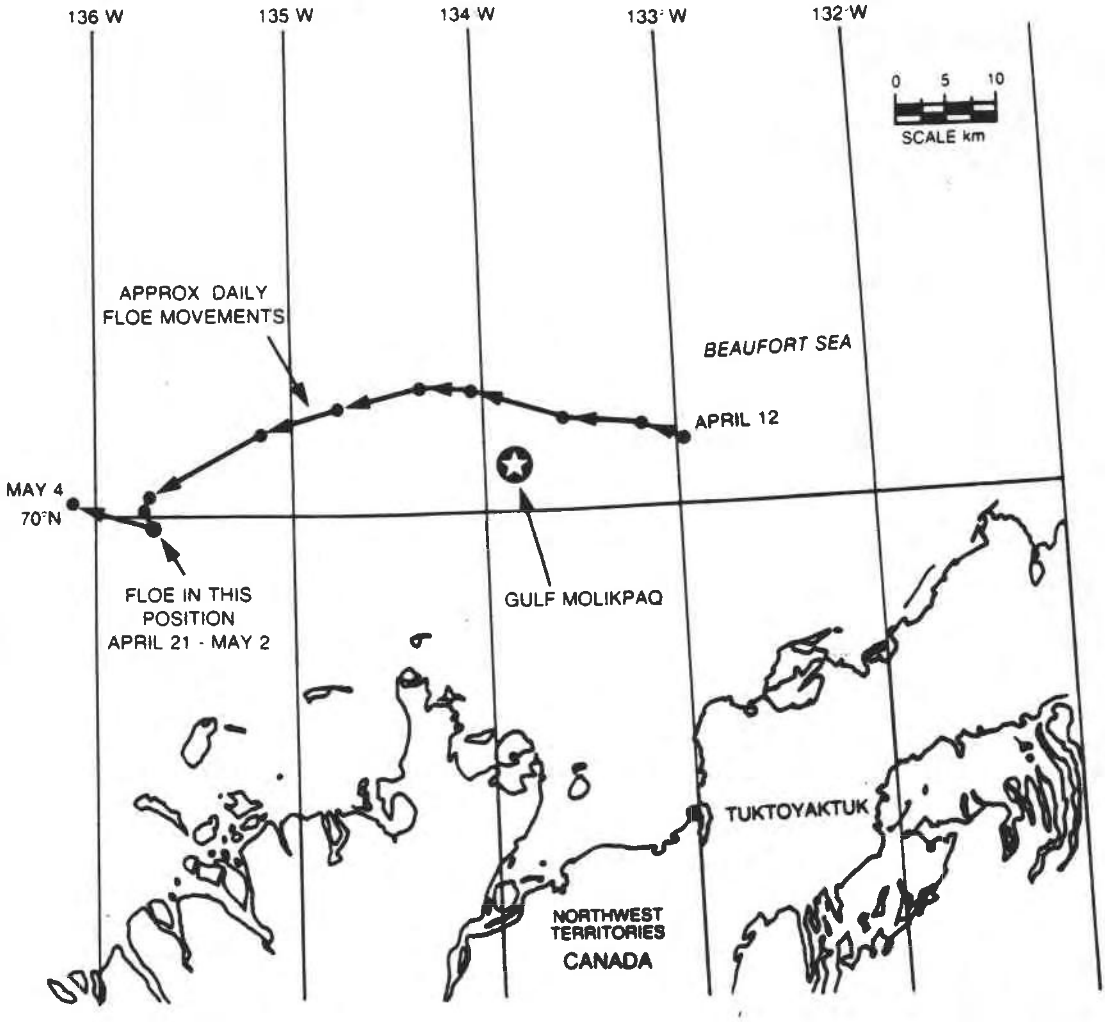


FIGURE 6: FLOE MOVEMENT DURING STUDY

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Commencing about April 20, the predominant wind direction changed from offshore to onshore. The floe became subject to a converging ice condition as the leads closed up and the pack ice was driven against the landfast ice. During this period, a series of apparent stress events were recorded. Several of these events could be correlated with the occurrence of new ridging in the first-year ice at the edge of the floe (see Figure 3).

The event which gave the highest stresses is shown in Figure 7. The maximum stress change was about 22 kPa. All the sensors in the Group 1 array responded to this event. Two of the sensors in the Group 2 array responded, but at lower levels. Another four stress events took place during the period April 21 to May 3. The signatures of the stress outputs were similar to those shown in Figure 7, but their magnitudes were lower.

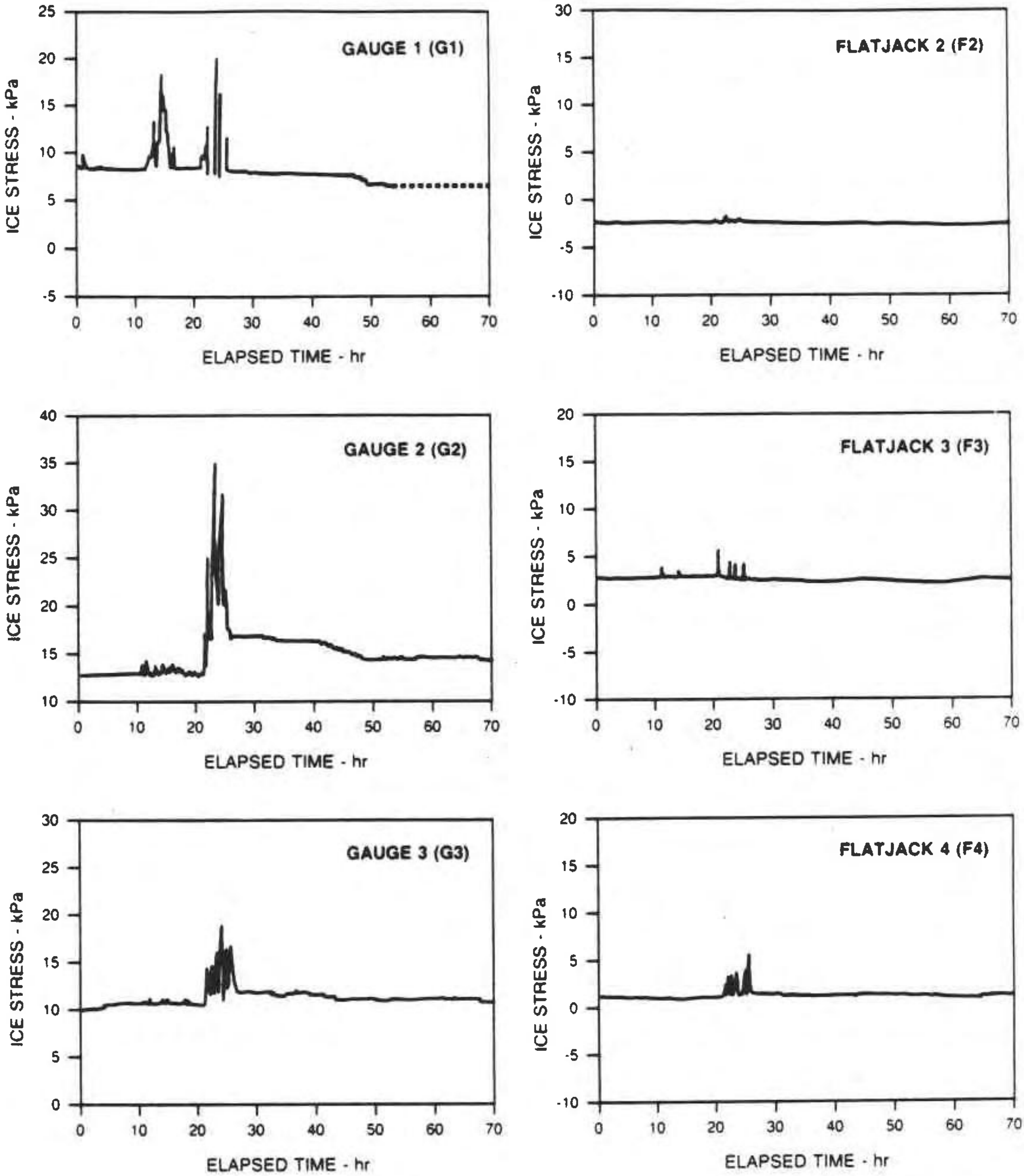

FIGURE 7: TYPICAL ICE STRESS EVENT
(START OF RECORD - 1550, 21 APRIL)

Discussion of Results

In this paper, a full presentation and discussion of results is not possible. However, the following can be concluded from examination of the results.

- o Although during the settling-in period, the sensors appeared to respond to thermal changes as well as stress events, the signatures of the responses were quite different. The thermal changes created outputs which correlated with variations in air temperature, whereas the stress outputs were spiky and similar to ice failure-stress signatures obtained in other situations. Also the outputs due to thermal effects became very small after the temperature transients had dissipated and a snow cover had re-established.
- o Between stress events, the outputs from the sensors were very constant, exhibiting virtually no drift. On removal, all but one sensor came back to within 2 kPa of the initial zero.
- o The stress events could be linked in almost all cases to new ridging around the floe. The highest stress event was linked to the creation of ridges with sails up to 4 m high.
- o Changes in floe motion, prior to it being subject to converging ice, did not generate measurable internal stresses in the floe.
- o There were problems of consistency of stress readings between the two arrays. It is not possible to be sure why these differences occurred. Possible explanations are;
  - Different sensors used in the two arrays,
  - Different installation methods,
  - The presence of cracks in the floe.

Interpretation of Results

The event shown in Figure 7 yielded the highest and most consistent stress outputs. It is of interest to expand the time scale for the gauge-type sensors during this event; this has been done in Figure 8. It will be noted that stress peaks from the three sensors in the rosette are not synchronous. This implies that the direction of principal stress is changing quite significantly with time. This is not unreasonable given that ridging events around the floe are probably not simultaneous across the 5 km of floe length. A point to recognize when examining the expanded time outputs is that ice stress was being measured once every minute. It is possible therefore, that some of the higher peaks have been lost. Looking at the nature of the traces, however, it is the authors' opinion that extensions to the recorded peaks due to this effect would be less than about 10 to 20%.

A simple interpretation of the outputs gives the highest recorded stress change as 35 - 13 = 22 kPa. This occurred on gauge 2 at about 1520 hours on April 22, see Figure 7. How can we interpret this in terms of an average compressive stress through the full floe thickness of 1.8 m? There are two corrections which must be made; one is in relation to the gauge inclusion factor, the other is in relation to the distribution of stress through the ice thickness.

As regards to the latter, we do not have enough information to quantify the stress distribution. In a more comprehensive experiment, at least two sensors, one above the other through the ice sheet thickness would give an indication of stress distribution. In this trial deployment this was not done. Another approach would be to calculate an ice modulus distribution through the ice thickness, based on temperature and salinity distribution. For strain compatibility, the distribution of ice modulus would be an indication of the stress distribution (assuming a uniform compressive load applied at the floe edge). In this experiment we did not obtain the temperature and salinity profiles, so this cannot be done.

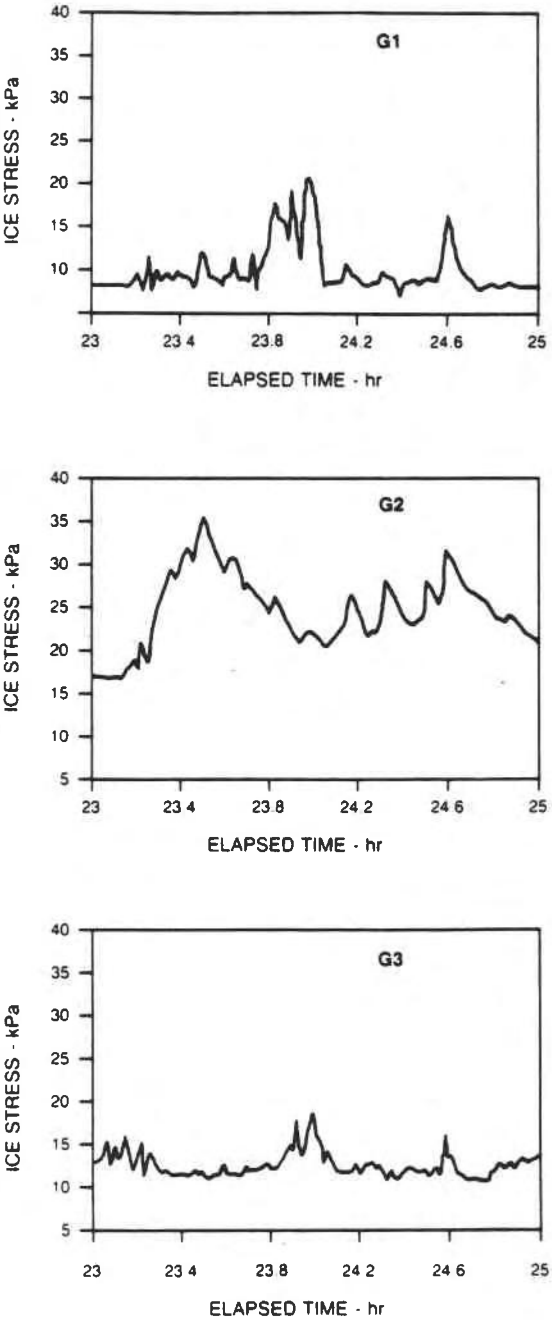

FIGURE 8: MAXIMUM STRESS EVENT - EXPANDED TIME SCALE

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We can speculate, however, that in view of the fact that the sensor was above the mid-point of the ice thickness, that it is probably reading a stress which is higher than the average stress through the floe thickness; how much higher is a matter of speculation. The authors' suggest that the sensor could be reading a stress which is no more than 1.0 to 1.3 higher than the average stress through the floe thickness.

The inclusion factor effect tends to push the measured stress in the other direction, i.e., lower. From the cold room tests it was concluded that the inclusion factor for the gauge sensors was in the range of 0.35 to 0.9. It was noted, however, that the inclusion factor tended to the higher value when the sensor had been pre-stressed for a number of hours. (Also, that the method of testing the sensors in finite ice blocks could have been a major cause of variation in the inclusion factor). For the event we are examining, the sensor had been under a compressive stress from the initial freeze-in, for several days, and from the beginning of the stress event for several hours. Therefore, it is suggested that the inclusion factor was probably closer to 0.9 than to 0.35. We will assume a likely range of inclusion factor is between 0.75 and 0.9.

We can now combine the two error bands. If σ is the nominal ice stress output, then the range of interpreted average compressive stress σ_c is given by

$$\sigma_c = \sigma \left[\frac{1}{0.9(1.3)} \text{ to } \frac{1}{0.75(1.0)}\right]$$

i.e., $\sigma_c = 0.85\,\sigma$ to $1.33\,\sigma$

In other words, the most likely value of highest average compressive stress through the floe thickness measured during this project was about 1.33 x 22 = 29 kPa, the lowest value of the peak stress event being about 0.85 x 22 = 19 kPa.

Based on these ranges of values for the peak compressive stress measured in the floe, what can we say about the average pack ice or ridge-building forces acting at the floe edge? The most simplistic interpretation is to assume a uniform floe with a uniform ridging or pack-ice force around it. In this case, the average ridging load (w) can be calculated as

$$w = \sigma_c t$$

where σ_c is the average compressive stress through the ice thickness (t), where the stress is measured.

Using this approach, with t = 1.8 m, yields

$$w = 29 \times 1.8 = 52 \text{ kN/m } (5 \times 10^4 \text{ N/m})$$

Such a value is quite compatible with the range of possible ridge-building forces shown in Table 1.

Note that for this project (but not presented in this paper), a series of different edge load distributions and floe thickness distributions were examined in relation to their influence on the compressive stresses at the floe centre. The work indicated that the potential error associated with the assumption of a simple uniform edge loading would generally be less than about ± 25%.

Other potential errors associated with the previous simple interpretation include the effects of active cracks in the floe.

With the limited nature of this trial experiment, it is not possible to quantify the possible magnitudes of the above potential errors. Their cumulative effect could be additive or balancing. At this stage, one might speculate that their effects, plus other potential errors already discussed, could give a total error band of about ± 100%. This would then lead us to the result that the maximum pack-ice forces or ridging forces measured during this experiment were in the range of about 0.25 to 1.0 x 10^5 N/m.

Concluding Remarks

This was the first project (at least in the public domain) to focus on the measurement of pack ice internal stresses, with the specific aim of obtaining average ridging forces across a wide front. It was a pilot project and it was recognized that limited resources for the field deployment would result in less than an ideal set of measurements, which would lead to uncertainties in interpretation. This proved to be the case, and yet, in the authors' opinion the results are plausible and for the first time typical internal stresses in a floe subject to limiting pack-ice forces (i.e., ridging forces) have been obtained.

Some difficulties were associated with construction of the sensors and the cold room tests. Problems associated with testing the sensors in large ice blocks included:

- Freezing-in the sensors without cracking the ice blocks and also ensuring that the ice was in intimate contact with the sensors.
- Applying a uniform stress to the ice blocks.
- Non-uniform stress distribution in the ice blocks due to variation in ice modulus caused by temperature variations in the ice blocks.
- The creation of internal stress in the ice blocks due to temperature variations in the ice blocks, these internal stresses being as great as the applied low stresses.

In hindsight, the temperature control in the cold room was probably much more critical than originally thought. Future cold room testing of low stress sensors should be done with the ice blocks under isothermal conditions.

In the field, the sensors appeared to respond better than in the cold room, in that drift was minimal and the outputs from the sensors was remarkably stable between the obvious stress events. This tends to support the suggestion that some of the perceived sensor problems in the cold room tests were due to the factors mentioned above.

On the other hand, the outputs from some of the sensors in the field were not consistent. In general, the outputs from the Group 2 sensors were lower than

Group 1 and some of the Group 2 sensors showed no response to stress events. It is speculated that this was primarily due to the installation method which was different for the Group 2 sensors than the Group 1 sensors, and could have resulted in incomplete contact between the sensors and the ice. However, the presence of cracks in the floe could also be a possible explanation for the lack of consistent agreement between the two groups of sensors.

The logistics of the field program proceeded very smoothly. Also, the data recording system functioned very well, with only some minor malfunctions (about 98% of the data was captured).

The measured values of the internal stresses in the floe during the ice stress events could be linked to the observed ridging events. No internal stresses were recorded when the floe changed speed or direction.

The results from this project are sufficiently encouraging to recommend that a more comprehensive field project be conducted. Ideally, the ingredients of such a project should be as follows:

- o It should be conducted in an area with a mixture of multi-year and first-year ice and which is fairly dynamic.
- o Two multi-year floes of different sizes should be instrumented, rather than one.
- o Each floe should be instrumented with at least two rosettes of sensors near to the centre of the floe, and with additional rosettes closer to the edges of the floe.
- o At least two levels in the thickness of the floe should be instrumented at each rosette.
- o Consideration should also be given to deploying surface strain meter rosettes as well as stress sensors.
- o The sampling rate should be more frequent than every minute (at least for some of the time, for some of the sensors).
- o Temperature and salinity profiles of the ice close to the sensors should be gathered.
- o The floes should be surveyed to give better thickness variation data than was possible in this project.
- o Ridges forming around the floes should be recorded in terms of ice thickness, profiles and extent.
- o The sensors used could be similar to those used in this project but there are some uncertainties associated with the sensors which still need to be addressed. A modest test program (building on the experience of cold room testing in this project) should enable the uncertainties to be resolved. This work should be done well in advance of the field work.

In summary, the project demonstrated that typical pack ice forces can be measured using an instrumented multi-year floe as a transducer. There remain some outstanding issues of interpretation which can probably only be resolved by conducting another field program as recommended above. However, the measurements obtained during this project will be of some help to scientists and engineers involved in pack ice modelling and ice force predictions.

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