

# **ALASKA OCS REGION**

# **Sea Ice Forces and Mechanics**

## **Conference Proceedings**

OCS Study MMS 87-0018

# **SEA ICE FORCES AND MECHANICS**

**Conference Proceedings**

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## INTRODUCTION

The Minerals Management Service (MMS) of the U. S. Department of the Interior has a mandate to manage the leasing, exploration, and development of oil and gas resources on the Outer Continental Shelf (OCS). The MMS must oversee these resources in a manner which is consistent with the following national needs: 1) to make such resources available to meet the Nation's energy needs; 2) to balance orderly resource development with protection of human, marine and coastal environments; 3) to insure the public a fair and equitable return on the resources of the OCS; and 4) to preserve and maintain free enterprise competition.

Alaska's Arctic Ocean, from the Bering Straits north and east through the Chukchi and Beaufort Seas, is ice-covered for much of the year. Sea ice creates a severe environment in the Arctic, with potential hazards for industry operations much greater than in the open ice-free ocean. Such hazards range from the forces that moving sea ice may exert against offshore structures, to interference with transport and offshore cleanup operations; from the icing of structures resulting from freezing spray, to gouging of the sea floor which may interfere with buried pipelines. In recent years, scientists and engineers have been working to gain a better understanding of these forces. This information becomes increasingly important when operations in the arctic offshore move from exploration to production, with the potential to build structures in deeper water, especially within the shear zone or pack ice.

From 1975 until 1983, the MMS, through an Interagency Agreement with the National Oceanic and Atmospheric Administration's OCS Environmental Assessment Program (OCSEAP), funded studies on environmental hazards, including sea ice characteristics and dynamics. Since that time, similar research has been funded by other Federal programs sponsored by the U. S. Geological Survey and the Department of Energy, as well as by the oil and gas industry. MMS also supports some continued work on ice forces and mechanics, especially related to the structural integrity of platforms, through its Technology Assessment and Research (TA&R) Program. The 1986 TA&R Annual Report states:

"In the Arctic, the TA&R Program continues to direct its efforts at determining the forces of the ice pack on structures. These forces may be less than previously considered a year or two ago, but additional field investigations are necessary to verify that conjecture. There are several variables that need to be quantified, all of which are not well defined. These include the mechanical properties of the multi-year sea ice, the wind and current shearing forces (which drive the ice against structures), the method by which ice fails (flexure and compression), and the contact stresses that ice exerts when it impacts structures. These are some of the technological areas now being examined."

The MMS Alaska OCS Region sponsored a conference on Sea Ice Forces and Mechanics in 1986. The intent of this conference was to present current technological theories and recent study data from several programs to MMS scientific staff and program managers for use in environmental assessment and field operations. MMS, with the assistance of MBC Applied Environmental Sciences, invited ten knowledgeable scientists to address other scientists and managers actively engaged in study or

## *Sea Ice Forces and Mechanics*

assessment of oil and gas activities in the offshore arctic environment. Invitees included representatives of federal and state agencies, academic institutions, and private companies in the U. S. and Canada. These proceedings summarize the presentations made at the conference.

There were two major categories considered during the meeting. Papers presented the first day focused on Sea Ice Forces. The talks covered how to measure the ranges of ice forces, which may impact structures; calculations of ice loads, which affect design criteria; fracture mechanics techniques for predicting ice loads on structures; field testing of compressive strength (one of the material properties of sea ice that impacts ice load analyses); and field observations of ice failure mechanisms, to improve understanding of the physics involved. All of these technical papers addressed the intricacy of the elements contributing to the physical forces exerted by sea ice, and added to the knowledge base for understanding these complex phenomena.

On the second day, papers addressed Sea Ice Motion and Mechanics. Following a brief review of the meteorologic and oceanic forces of arctic seas, detailed papers discussed large-scale forces from winds and currents, which also help determine ice loads on structures. Studies designed to provide this kind of data, such as the Arctic Buoy Program, were then described, and the need for ice stress measurements in the field was discussed. A few structures in other parts of the world have been instrumented to provide data on ice forces, and some of these were described. These kinds of data may be useful in formulating models to help predict ice loads upon structures. Finally, related questions of drifting ice islands and spray icing on structures were briefly addressed.

This report includes short papers prepared by each of the invited technical experts, summarizing their presentations at the conference, with accompanying graphics and reference lists for those interested in more in-depth information. Selected bibliographies on related topics and a list of attendees are included as appendices.

**PAPERS ON  
SEA ICE FORCES**



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# LIMIT FORCE LOADS AND MEASUREMENTS OF PACK ICE DRIVING FORCES IN THE BEAUFORT SEA

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## INTRODUCTION

In recent years, scientists and engineers have worked to gain a better understanding of ice forces on arctic offshore structures. Global ice forces can be considered in terms of limit-stress loads, limit-momentum loads, and limit-force loads. The definitions of these three limits have been discussed by several authors; they are described conceptually in Figure 1.

To date, most attention and research has been aimed at the first two limits referred to above, whereas research into limit-force loads has been minimal. Yet limit-force loads become increasingly important as operations in the arctic offshore move from exploration to production and as structures are built in deeper water, in the shear zone and in the pack ice.

The simplified concept of a limit-force load is that of a large, locally thick multi-year floe lodged against a structure. The major driving forces on the floe are caused by ridging in the pack ice behind it. If this integrated force is less than that required to locally fail the thick ice in front of the structure (the limit-stress load), then the design ice load will be less than is presently calculated on the basis of limit-stress.

Unfortunately, our state of knowledge of average pack ice or ridge-building forces across the width of a large floe is very rudimentary. The range of uncertainty in pack ice forces is at least a factor of 10, and possibly 50. Figure 2 shows some of the sources of data for ridge-building forces and demonstrates the large range of uncertainty.

At the same time, the potential benefits in better quantifying pack-ice forces may be significant. Figure 3a compares limit-force loads as a function of ridge-building forces with limit-stress loads for two different structures and interaction scenarios. Clearly, if average ridge-building forces across a wide front can be shown to be less than  $10^5 \text{Nm}^{-1}$  with a 100 KN/m, then reductions would be possible in the design ice loads for the winter interaction scenario.

It should also be recognized that momentum exchanges during the collision of a floe surrounded by pack ice with a structure are strongly influenced by the driving forces on the floe. This special case of the limit-momentum load cannot be properly quantified without better values for pack-ice forces.

In the past, ridge-building forces have been addressed using analytical models and by model testing. The objectives of the described project were to assess whether measurements of ridge-building or pack-ice driving forces could be successfully measured

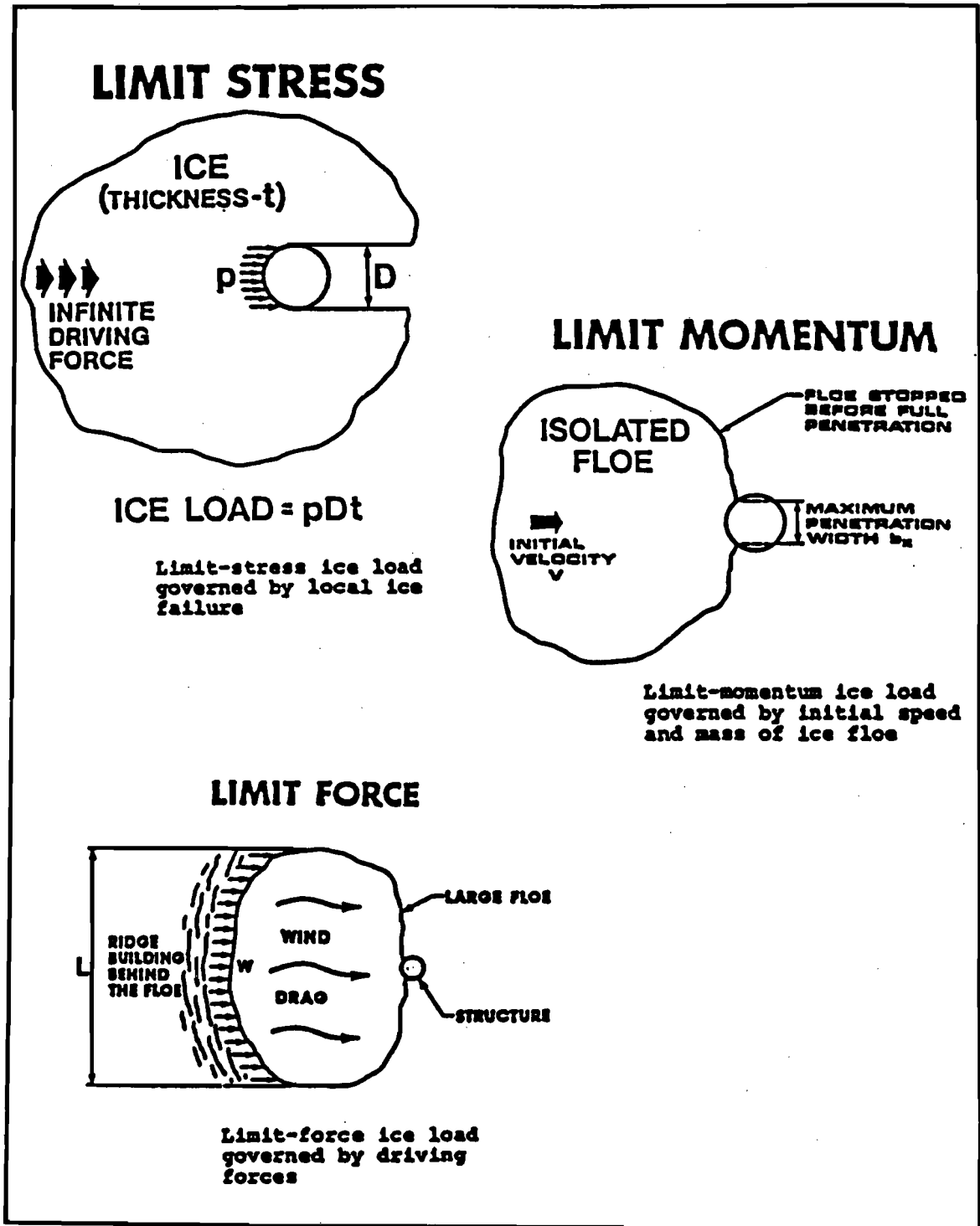


Figure 1. Conceptual description of global ice-force limits.

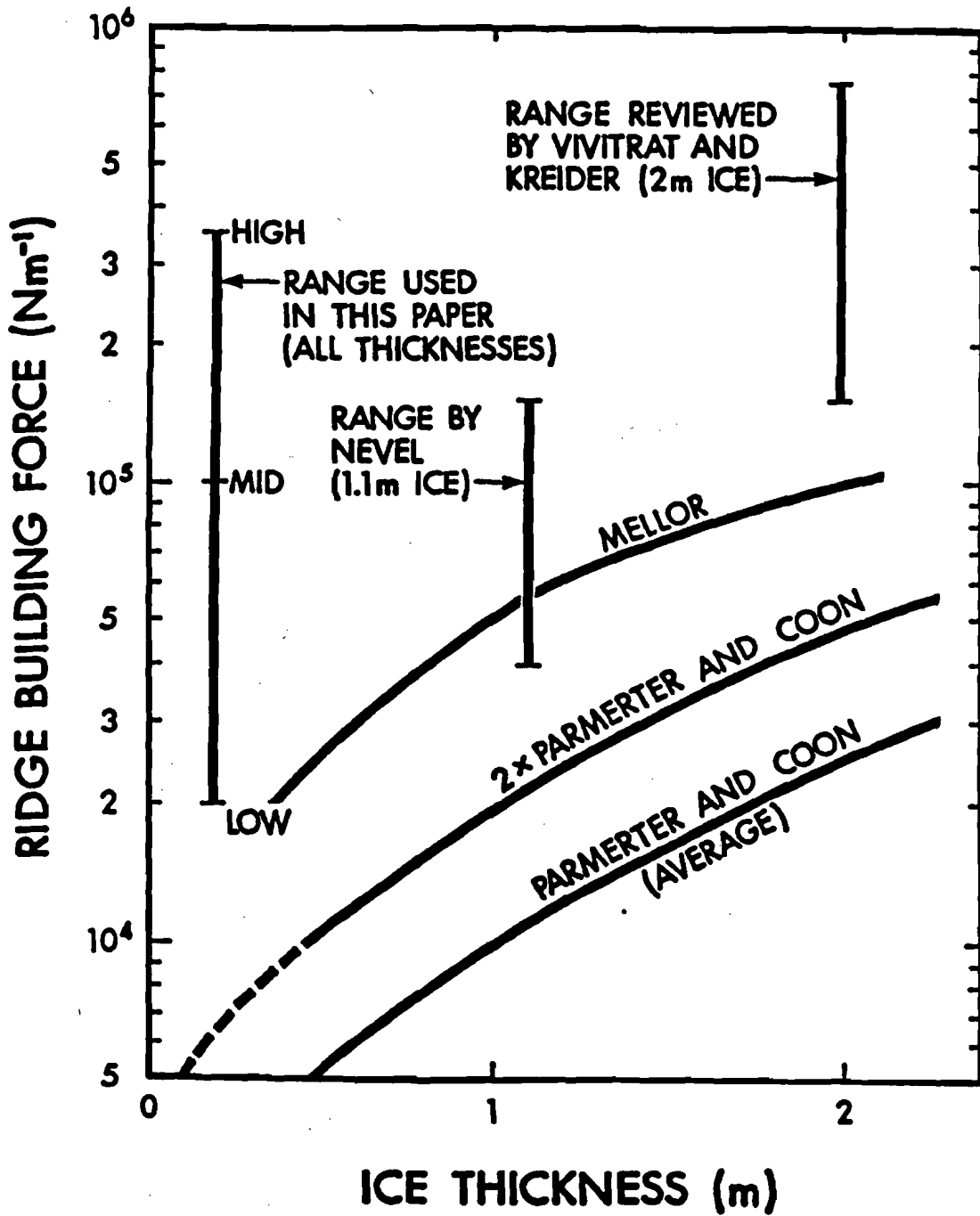


Figure 2. Estimates of ridge-building force.

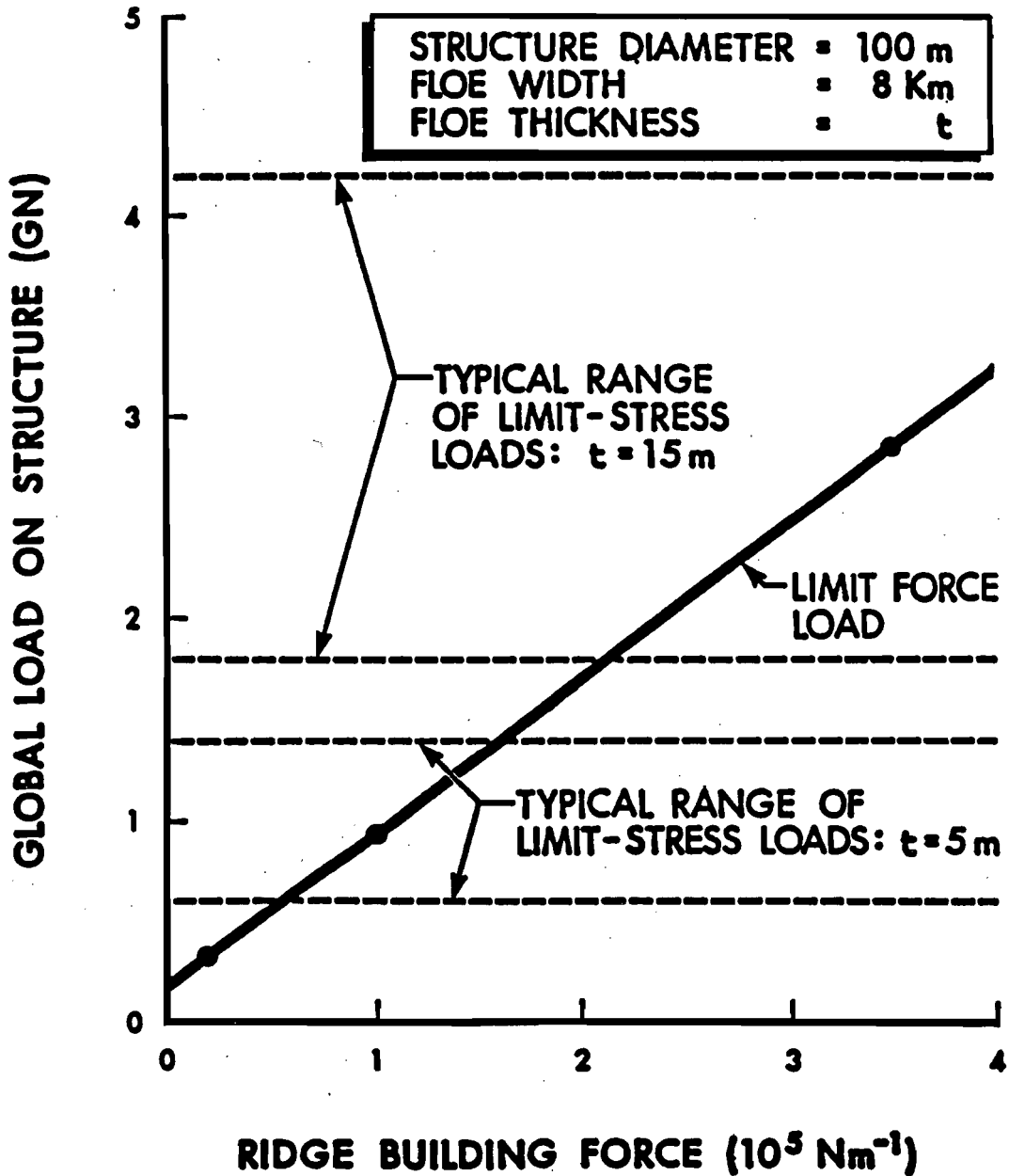


Figure 3a. Limit-force loads for two different structures and interaction scenarios.

in the field and to conduct a trial deployment. The work was funded by the Canadian Government (Department of Fisheries and Oceans and through the Unsolicited Proposals Fund); Gulf Canada Resources Ltd. provided some logistical support.

### OVERALL APPROACH AND ISSUES AFFECTING FEASIBILITY

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 center of a multi-year floe in an area of converging pack ice; this is shown conceptually in Figure 3b. In terms of the overall approach there are three major technical issues which have to be addressed and satisfied:

- Ability to reliably measure low ice stresses,
- Ability to interpret stresses measured at the floe center in terms of pack ice forces at the perimeter, and
- Confidence or knowledge that the pack ice forces experienced are typical maximums, or can be related to the ridging of ice of a specific thickness.

During the course of this project, the first issue was addressed by developing, and testing in a cold room, ice-stress sensors suitable for measuring ice pressures in the range of 0 to 100 kPa (15 psi). The second issue was partly addressed before going to the field by preliminary math modeling. But it was recognized that all of the above issues could best be assessed by conducting a trial experiment in the field.

### THE FIELD EXPERIMENT AND TYPICAL RESULTS

A trial deployment of two arrays of low stress range sensors was conducted between April 11 and May 4 in the Canadian Beaufort Sea. The instruments were installed near the center of a multi-year floe approximately 2.5 km by 5 km in size. The floe was initially in about 30 m of water and had been tagged with an ARGOS buoy by Gulf Canada.

During the course of the study, the floe moved about 60 km from east to west (Figure 4). For about 10 days the floe was in a converging ice situation, and during this period ridging events occurred on one side of the floe. Internal stress measurements were obtained which can be correlated to the ridging events. The maximum internal stress measured was about 30 kPa (4.5 psi). The sensors were placed where the floe was 2 to 3 m thick. Data gathered from the experiment have been analyzed and are reported in Croasdale *et al.* 1987.

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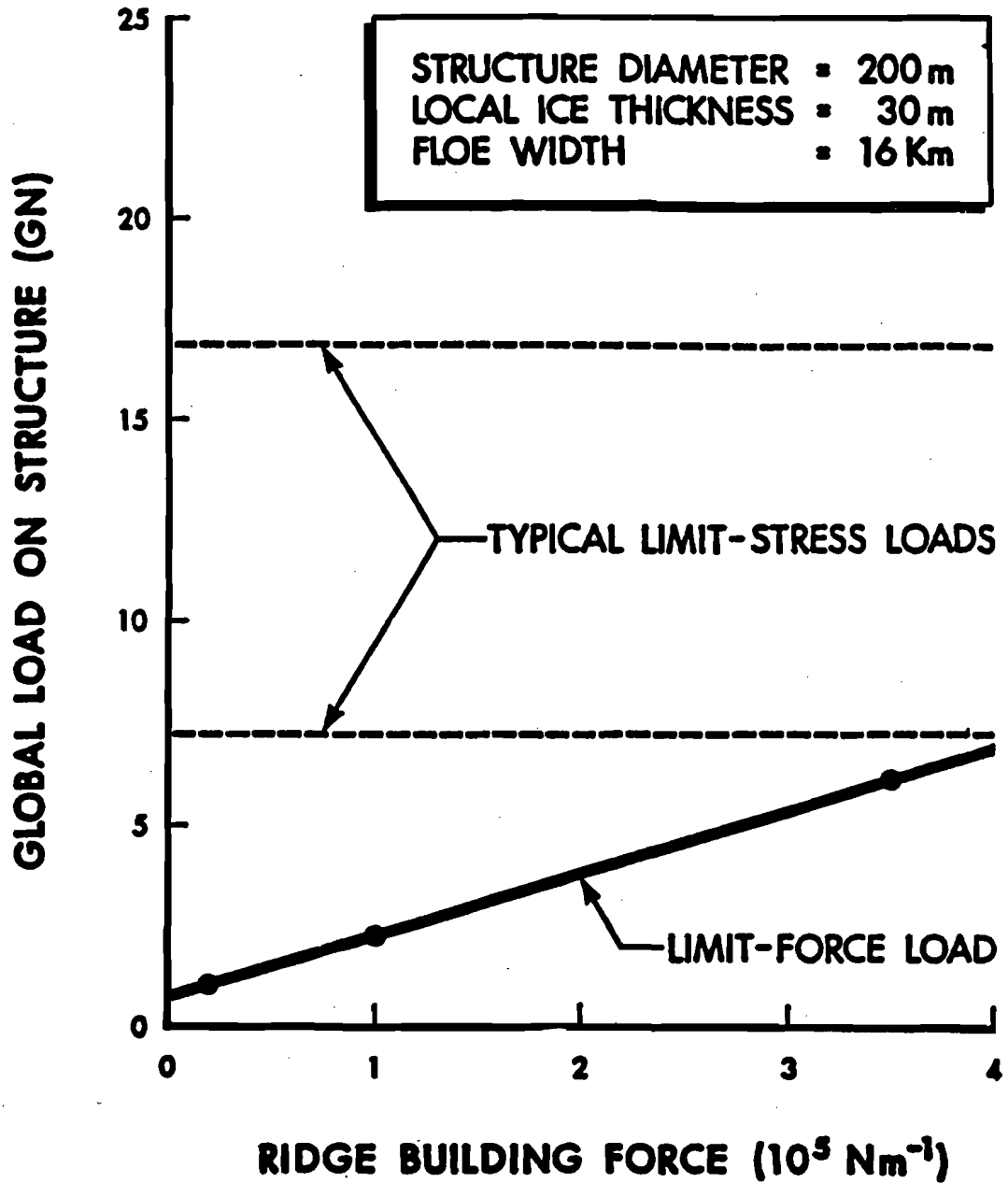


Figure 3b. Conceptual model for measuring pack ice forces.

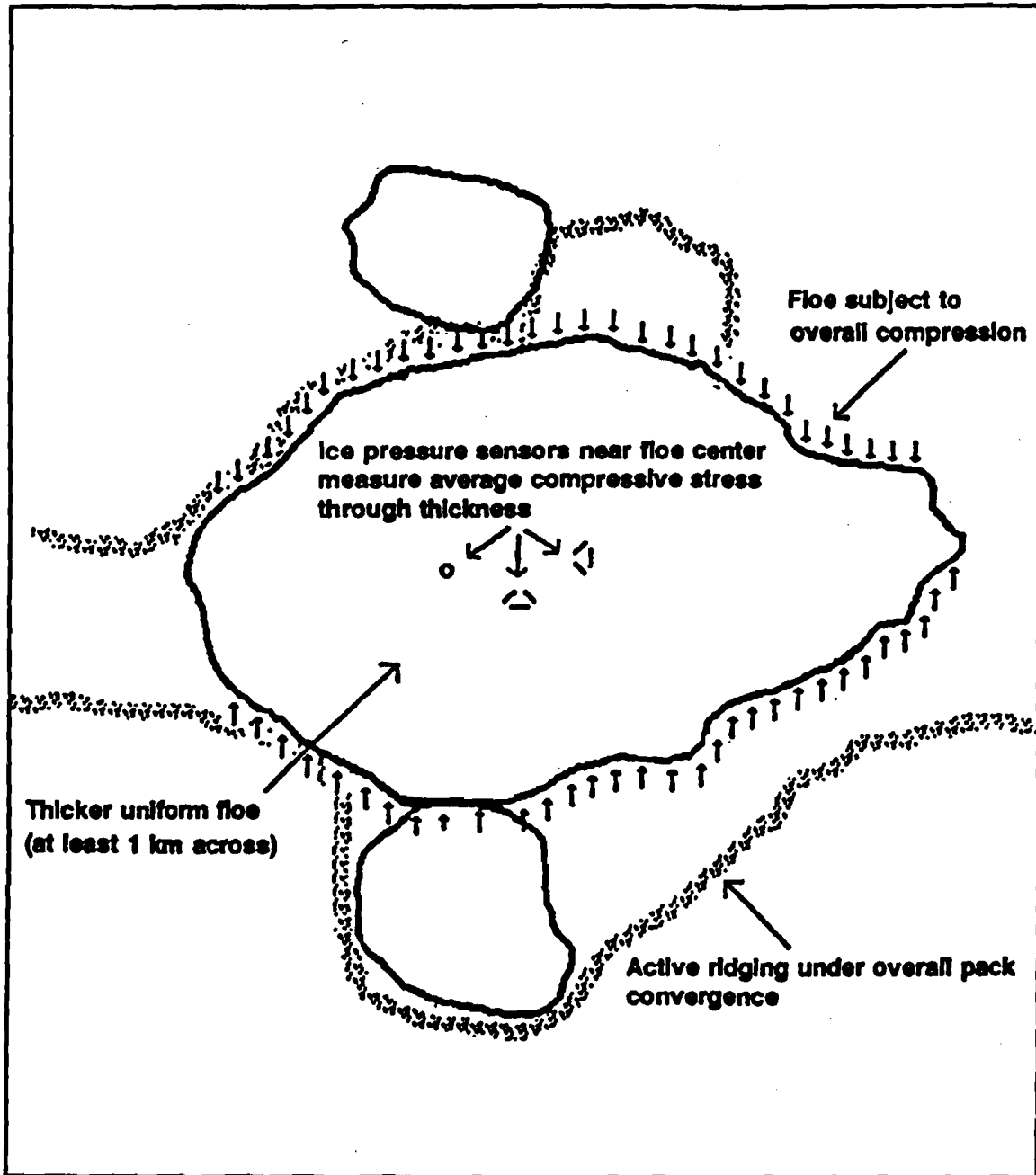


Figure 4. Overall scheme for measuring pack ice forces.



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# GLOBAL AND LOCAL ICE LOADS FOR STRUCTURE DESIGN

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## INTRODUCTION

In arctic and many subarctic environments, ice loads are the dominant design criteria. This paper discusses the philosophy of calculating ice loads over varying areas, as well as the effect of dynamics and loading rate.

The well-known aspect ratio effect allows for a reduction of effective ice crushing pressure as the aspect ratio increases, where:

$$\text{Aspect Ratio} = \frac{\text{Width of Ice-structure Contact}}{\text{Height of Contact}}$$

This relationship works well for floes, but the geometry of ridges is more complex and requires that additional modes of failure be calculated. Local ice pressures are a function primarily of the following:

- Ice types (sea ice, glacial ice, etc.),
- Temperature and salinity of the ice,
- Geometry of the ice feature (floe, ridge, etc.),
- Geometry of the structure (slope, width, floaters or fixed, etc.); and
- Rate of loading (impact, creep, etc.).

This pressure may be calculated according to the following:

$$F = \max \left[ F_{LD}, \min (F_{LS}, F_{KE}) \right] \quad \max \left[ F_{LD}, \min (F_{LS}, F_{KE}) \right]$$

where:  $F_{LD}$  = the "limit environmental driving force" on a structure, the summation of ridging plus wind and current shear over a floe lodged against a structure;

$F_{LS}$  = the "limit stress force" on a structure, the failure force of a floe across the full width of the structure (e.g. crushing, flexural failure, clearing, etc.); and

$F_{KE}$  = the "limit kinetic energy force" on a structure during impact, the peak force generated during the dissipation of the kinetic energy of the ice feature, including added mass effects.

The reduction in ice pressure with increasing aspect ratio reflects the following phenomena:

- Confinement effects over small areas or aspect ratios of 0.1 or less,
- Indentation geometry effects for aspect ratios up to about 4,
- Multi-zonal effects for aspect ratios in excess of about 6,
- Non-simultaneous contact,
- Multi-modal effects for large aspect ratios, and
- Ridge building effects for very large aspect ratios.

The non-simultaneous contact over the contact zone also accounts for much of the dynamics of ice loadings, as crushed ice "flakes" off and is moved or cleared. The response of the structure and foundation, as well as the velocity, are also important factors in calculating the dynamics of ice loads. Rubble fields affect the global ice loads due to the following effects:

- The introduction of multi-modal failures,
- The transfer of load to the seabed, and
- The increased width due to the presence of rubble.

#### SCALE AND SIZE EFFECTS

There are several formulations of ice pressure versus aspect ratio-area from which both global and local ice forces can be determined. There are also specific theoretical formulations that apply only to certain classes of ice loading (e.g. flaking theory over small areas; aspect ratios and ridging theory for large aspect ratios). Afanas'ev (1972) developed the following equation, based on non-simultaneous contact:

$$F = m \sigma_c D h (5h/D + 1)^{0.5}$$

where:  $m$  = shape coefficient  
 $\sigma_c$  = uniaxial compressive strength  
 $D$  = width of indenter  
 $h$  = ice thickness

In a recent paper (Ashby and Palmer *et al.* 1986), the following expression is given for ice crushing pressure:

$$p \propto 1/A^{0.5}$$

where:  $p$  = pressure on structure  
 $A$  = contact area

In developing this equation the authors use an analogy with brittle foam. Since unreasonably large cracks would be required to explain this with fracture mechanics, the authors conclude that the size effect is not the result of flaws, but is due to non-simultaneous failure.

The square root of area is also quoted by Churcher, Johansson and Duff (1985) as:

$$p = C/A^{0.5}$$

In a controversial paper by Bohon and Weingarten (1985), a novel interpretation of Korzhavin's equation was proposed:

$$F = DtIK \sigma_c$$

where: F = force on the structure  
t = ice sheet thickness  
I = indentation factor  
K = contact factor  
 $\sigma_c$  = uniaxial compressive strength of ice

A normalized uniaxial compressive strength was shown to peak at  $2 \times 10^{-3} \text{ sec}^{-1}$ , and a new definition of strain was proposed:

$$e = \begin{cases} V/4D & \text{for } 0.5 > D/t \\ VD/t^2 & \text{for } 0.5 \leq D/t \leq 2.0 \\ 2V/t & \text{for } 2.0 \leq Dt \end{cases}$$

A normalized peak indentation pressure versus aspect ratio was presented which is similar to that of Afanas'ev (1972). Sasajima *et al.* (1981) compare experimental results with Korzhavin (1962) and Afanas'ev (1972), and Saeki *et al.* (1979) show that the force on a pile is:

$$F = Ch scW^{0.5}$$

where: F = ice force on a pile  
C = shape factor  
h = ice sheet thickness  
 $\sigma_c$  = uniaxial compressive strength  
W = width of pile

Kry (1978) demonstrated a method of simulating ice loads over multi-zones.

A design curve from the Esso, Gulf and Dome Environmental Impact Statement (EIS) (Dome 1982) is shown in Figure 1, which encompassed the range of aspect ratios from 0.1 to 100,000. The thinking that went into the formulation of this curve incorporated small scale tests, field tests, artificial island sensor measurement results, Hans Island preliminary data, and large scale Arctic Ocean internal pressure-dynamics considerations.

Global ice loads on East Coast, gravity-based structures under iceberg impact were quoted by Johnson and Nevel (1985) as:

- Smooth cylinder: F100 year = 2,000 MN
- Pointed geometry: F100 year = 1,600 MN

Global ice loads on a drilling structure in the Beaufort Sea can be quoted from Hnatiuk and Felzien (1985) as  $F = 500 \text{ MN}$ , after one drilling seasons. The EIS curve as shown in Figure 1 can be used for both local and global ice loads but the reader should

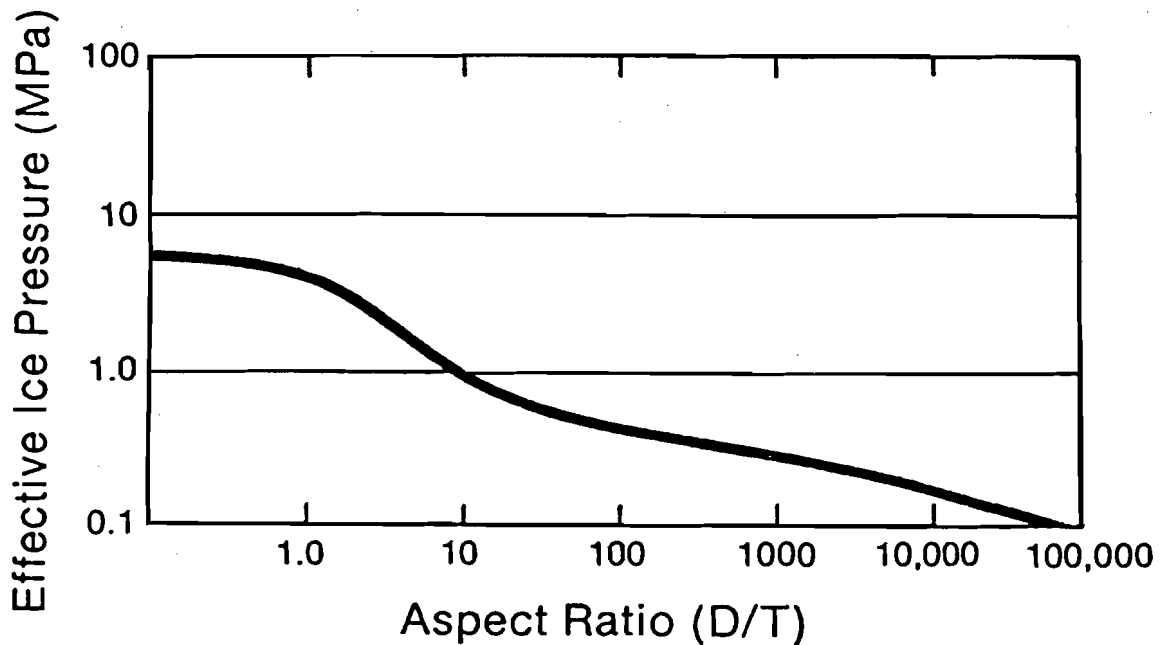


Figure 1. Pressure versus aspect ratio curve.

be cautioned not to use it directly, as it was developed in 1982 and does not reflect recent full-scale data.

### DYNAMICS

Ice-structure-soil dynamics are known to influence structure designs and water depth combinations where large rubble fields do not accumulate and where ice-structure contact occurs for thicker ice features. Dynamic models have been developed for three areas: Cook Inlet, the Baltic Sea, and earthquake prone areas.

Matlock (1969) developed a model for analyzing ice-structure dynamics. The structure is represented by a spring mass system and ice is replaced by a succession of elastic brittle elements which impinge on the structure at a rate determined by the relative motion between the ice and the structure. The Hondo Bridge was instrumented and reported on by Montgomery, Gerard and Lipsett (1980). More recently a Norwegian research report (Bjork 1981) addressed the problem of dynamic ice loading in a paper entitled "Ice Induced Vibration of Fixed Offshore Structures". A doctoral thesis from the University of California dealt with the problem of ice-structure-soil interaction under the action of earthquakes (Croteau 1983).

The work on earthquake analysis has been expanded by Swan Wooster to account for grounded rubble, including the possible effect of freeze bond between the rubble and the structure. There are also several recent papers on stochastic methods. However, the underlying linear assumptions are generally too restrictive to effectively model actual soil and ice nonlinearities. Three levels of complexity are identified in the ice-structure-soils models:

- Simple nonlinear models (time domain),
- Stochastic models (frequency domain), and
- Complex non-linear models using finite elements (time domain).

### PROBABILISTIC METHODS

Two distinct examples of probabilistic approaches are presented by Allyn *et al.* (1985).

#### Monte Carlo Simulation

- Construct probability distributions of ice environmental parameters,
- Generate a number of random ice features, such as eccentric hits,
- Use a deterministic model to calculate the discrete ice-structure interactions, and
- Rank the loads and plot them to Lognormal, Gumbel, Weibull, etc. scales.

Figure 2 shows a Gumbel plot generated by Swan Wooster's computer programs (Allyn 1986).

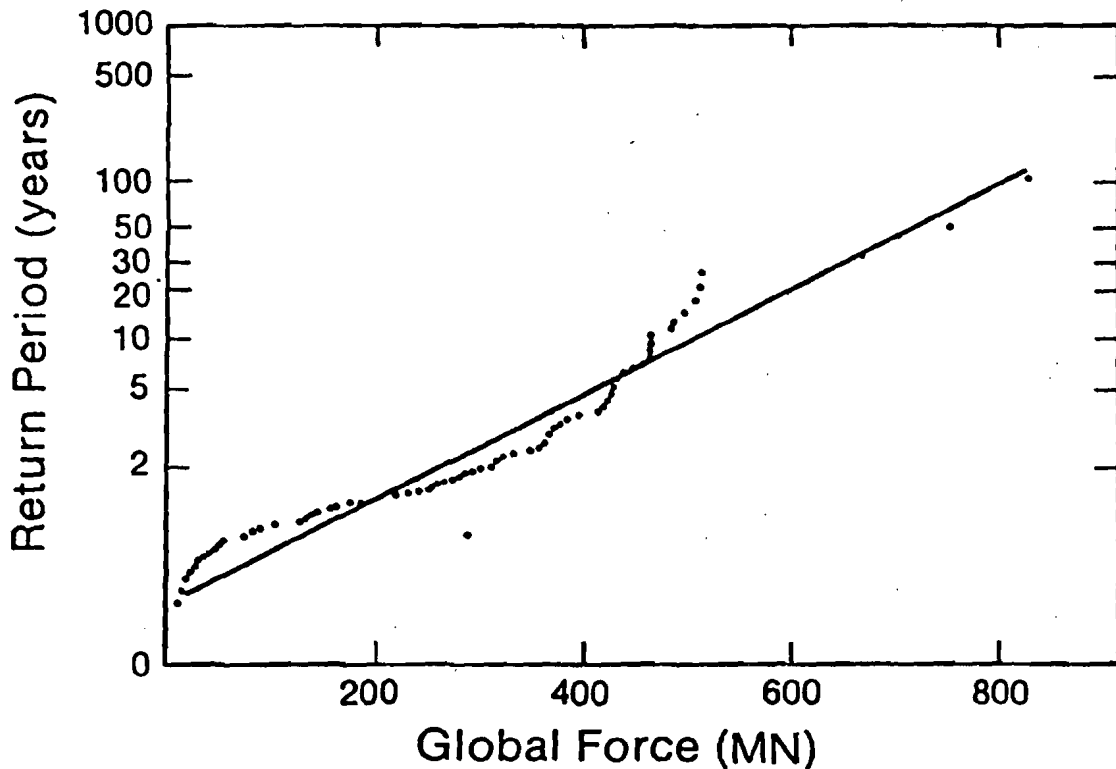


Figure 2. Global force versus return period.

## Floe Class Studies

The governing equation is:

$$P(v/h,d) = (TN P(d)P(h/d))^{-1}$$

where:  $P(d)$  = probability of a floe being of a floe class with diameter  $d$   
 $P(h/d)$  = probability of a floe being of a floe class with thickness  $h$   
 $P(v/h,d)$  = probability of a floe being of a floe class with velocity  $v$ ,  
given  $h$  and  $d$   
 $T$  = return periods in years  
 $N$  = number of floe impacts per year

The probabilities are given as conditional, but the available data are for independent distributions, which is what is used. The ice forces from a range of floes with varying diameters, velocities and thicknesses are calculated, all with a constant return period. This method is very useful for quickly assessing the governing ice characteristics.

Dunwoody (1983) shows how ice feature diameters and velocities should be weighted to account for the statement that "a structure is more likely to be hit by a large diameter or fast moving ice feature than a small diameter or slow moving ice feature." Dunwoody also shows how to perform multiple integration to determine a probability distribution for kinetic energy.

## RIDGE LOADS

Ridge loads are calculated numerically using mechanisms observed in physical model tests as presented by Lewis and Croasdale (1978). For analysis, an elastic bending plus torsion beam on elastic foundation model is used, with an initial crack followed by hinge cracks. A principal tension failure criterion may be used which combines bending tension, torsion shear and bending shear stresses. The bending mechanism described above does not account for other modes that may occur when the ridges are short:

$$L = \pi \lambda / 4$$

where:  $L$  = ridge length  
 $\lambda$  = characteristic length of the ridge

A "flaking" mechanism has been developed by Swan Wooster to limit the loads for short ridges. Other modes of failure include:

- In-plane flexural failure for vertical columns, and
- Passive pressure and shear planes for loosely bonded first year ridges.

Through-thickness properties include temperature and salinity profiles, which can be determined from coring data and which can yield salinity, tensile strength and modulus of elasticity variations with depth (Frankenstein and Garner 1967, Vaudrey 1977). Swan Wooster's suite of computer programs, for example, calculates these through-thickness properties and the upward and downward cracking moments by using a 'slice' method, with 10 slices in the ridge sail and 20 slices in the ridge keel.

## FLOE LOADS ON CONES

Floe loads on cones have been formulated for upward and downward breaking sloping surfaces (Ralston 1979). The force components are associated with:

- Radial cracks,
- Circumferential cracks,
- Lifting/submerging blocks of ice, and
- Clearing blocks of ice.

As for ridges, the through-thickness salinity and temperature distributions are available from coring data. These are translated to upward and downward cracking moments using the method of slices. A step-by-step simulation is conducted in Swan Wooster's computer program as shown in Figure 3.

## RUBBLE FIELDS

As discussed by Allyn and Charpentier (1982), rubble fields may be one of the most important factors in the design of arctic offshore structures for the following reasons:

- They may induce multi-zonal failures due to their width, and the ice floe/rubble interaction pressures are reduced as compared with traditional calculations of the ice floe-structure interaction;
- They may induce a multi-modal failure of the incoming ice due to the random block orientations within the rubble pile which further reduces the pressures;
- Grounded rubble reduces the force that can be transmitted to the structure by the pack ice;
- The energy absorption capacity of a rubble field may be large; and
- The physical extent of a rubble field can be a hindrance to access by tankers and supply vessels.

Consideration of the possibility of ice rubble forming a part of exploration structures has developed from observations of apparently stable rubble fields which develop annually over submerged remnants of abandoned artificial islands, and natural shoals such as Katie's Floeberg (12 m deep) and the Natural Shoal (15 m deep). These features could perhaps protect a winter drilling system with minimal additional structural cost, although a year-round drilling or production system must still contend with summer storms and ice intrusions as well as freeze-up and break-up. To further examine the implications of these observations, Swan Wooster has developed a computer program which accounts for these important variables in a complex ice-structure interaction and provides a chronological record of extent and resistance of ice pile-up. A rubble-protected drilling system, using inexpensive rubble generators and sprayed ice, is proposed as a method of reducing exploration drilling costs in water or berm depths of up to about 20 m.



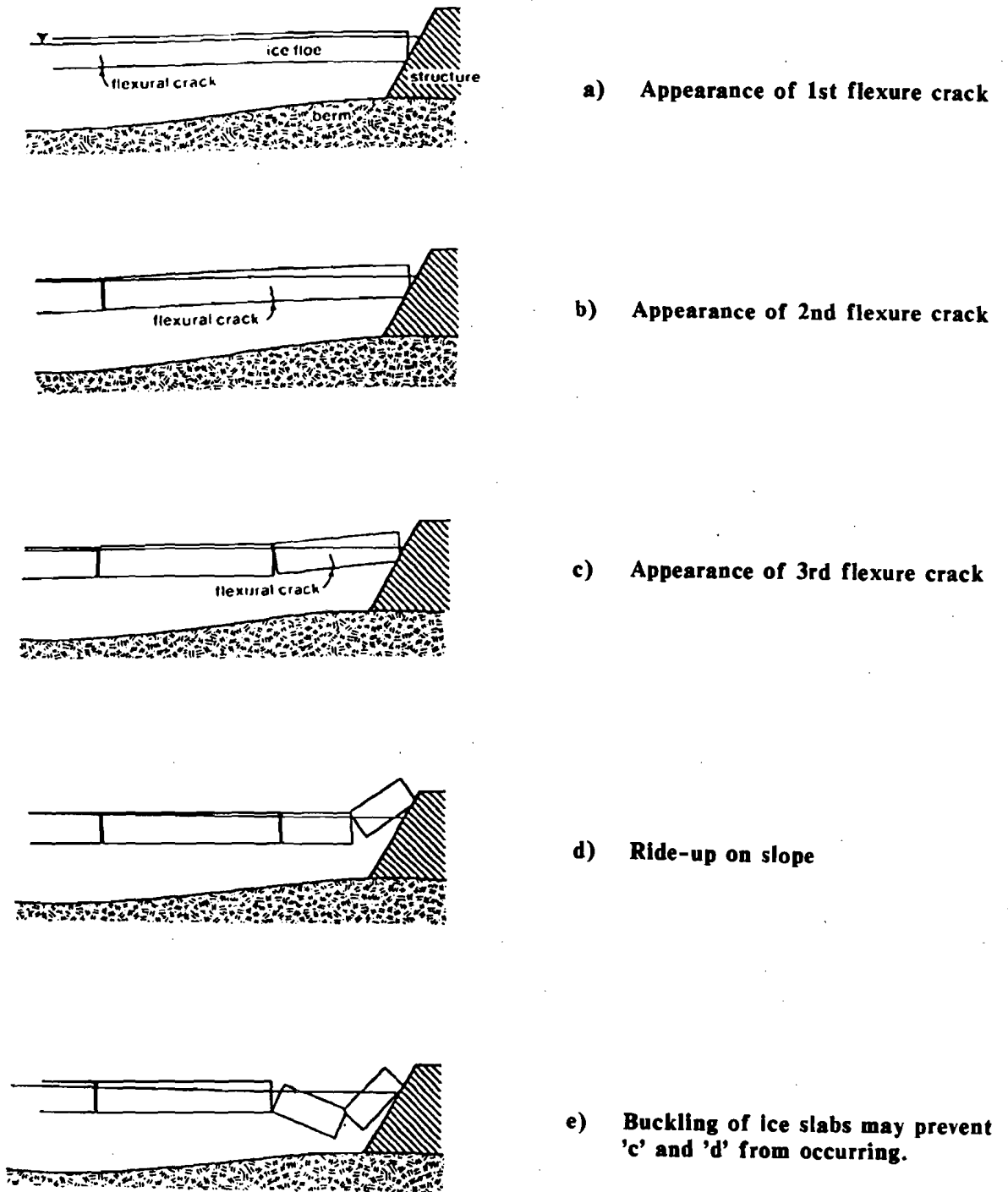


Figure 3. Ice sheet failure on a sloped face.

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# NEW RESULTS IN ICE LOAD PREDICTIONS USING THE FRACTURE MECHANICS APPROACH

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## INTRODUCTION

Traditionally, the engineering approach to ice-load predictions has been based on the concept of the compressive and tensile strength of ice. This concept has proved useful in describing strength and failure of laboratory ice specimens and in predicting ice resistance in small-scale indentation tests. At the same time, there has been ever-growing evidence that fracture mechanics methods must be used to describe gross cracking and fragmentation of ice sheets. In this note, a brief overview is presented on the recent progress in applying linear fracture mechanics to ice-load predictions.

Failure of ice can be classified in a very broad sense into two categories:

- Failure in compression (all principal stresses are compressive), and
- Failure in tension or shear (at least one principal stress is tensile).

## OVERVIEW OF FRACTURE MECHANICS

Failure of ice in compression is often referred to in the literature as crushing failure. Crushing can be regarded in the macro-scale as a continuous process of deformation. However, on the level of micro-mechanics, this type of failure results from the nucleation, propagation and linkage of micro-cracks in ice. The micro-cracks initiate as the so-called wing cracks at the grain boundaries or the edges of randomly oriented flaws. Initially they grow in a stable way as the overall compressive stress increases until the instability point is reached and an overall failure of cracked body takes place. A fundamental study on the growth of a single wing crack in the sheet of an elastic-brittle material was made by Nemat-Nasser and Horii (1982). Ashby and Hallam (1986) and Sammis and Ashby (1986) extended the analysis by developing a condition for a critical length of wing cracks at which a complete loss of strength and stiffness takes place. Those results utilizing fracture mechanics methods form a rigorous basis for developing failure criteria for ice in plane stress or plane strain situations. Previously, yield or failure conditions for isotropic and anisotropic ice (such as Coulomb-Mohr) were constructed on a purely empirical basis (Karr *et al.* 1988).

The existence of fractured surface in polar pack ice in the form of leads, rubble piles, pressure ridges, etc. indicates that there has been an intense tensile or shear fracture activity in ice sheets. Several typical modes of ice fragmentation (including spalling, radial cracking, and splitting) were identified and preliminary analyses of the propagation of various forms of cracks have been offered (Ashby *et al.* 1986, Ashby *et al.* 1986, Thousless *et al.* 1986, Wierzbicki and Karr 1988).

The problem of tensile fracture of elastic-brittle ice is a relatively simple one in fracture mechanics once the far-field tensile stress and the initial length of the crack are known. A number of manuals and tables of stress-intensity factors are available in the literature for various shapes of free boundaries and various loading configurations.

Unfortunately, neither the tensile stresses nor the size of the "starter" crack can be easily determined in most ice loading situations. This includes the problem of a floe-to-floe interaction, locking of a large moving multi-year floe, and compression of packed ice. The fracture process usually starts from the local crushed or compressive zones. There must be a transition from compression to tension before a gross tensile crack can be propagated away from the stressed zones. The transition process can be studied numerically by considering the elastic-plastic softening model of ice. A simplified method was adopted by Palmer *et al.* (1983) and Wierzbicki *et al.* (1988) to study the propagation of radial cracks in ice sheets. The reasoning behind this method is as follows.

Suppose an initial contact has been established between the ice sheet and the structure. In plane stress or plane strain cases, all components of stresses are initially compressive. Micro-cracks will be formed and will grow under increasing load until failure in compression takes place in the stress zones. The size of the damaged zone will grow and the material within this zone is assumed to be completely crushed, thus being able to transmit hydrostatic pressure only. As soon as the damaged zone spreads into a semi-circular region, the hydrostatic pressure exerted by the crushed material produces an edge-opening force which, under certain conditions, can run an edge crack into the elastic region. This situation is illustrated in Figure 1, where a new conceptual feature is that the width of the crushed zone ( $2R$ ) is not determined by the width of the structure ( $D^0$ ), but by the shape of an uneven leading ledge of the ice floe.

Another major obstacle in applying fracture mechanics methods to ice-load prediction is the initiation of cracks in an uncracked material. Recent work by Li and Liang (1985) on the transition from a strength to a fracture criterion in concrete has formed a much-needed basis for studying the process of fracture initiation in ice. Their approach was based on the concept of the existence of a process zone at the crack tip which obeys a stress-separation constitutive behavior with softening. Another promising approach to the initiation of splitting failure of ice sheets has recently been proposed by Wierzbicki *et al.* (1988).

#### APPLICATIONS OF FRACTURE MECHANICS

Having settled the fundamental questions, ways have been opened to determine the forces exerted by large, moving ice floes on structures or failure stresses in polar pack ice. Assuming, for example, that the impacting floes fail just by the splitting mode, shown in Figure 1, then the so-called pressure area curve can be constructed following the solution presented by Wierzbicki and Karr (1988). The theoretical solution is compared in Figure 2 with experimental points (including Hans Island experiments) collected by Sanderson (1986). The agreement is seen to be very good.

Encouraged by the success of the present methodology, we are currently working at MIT on the solution of ice splitting problems for several typical loading configurations including:

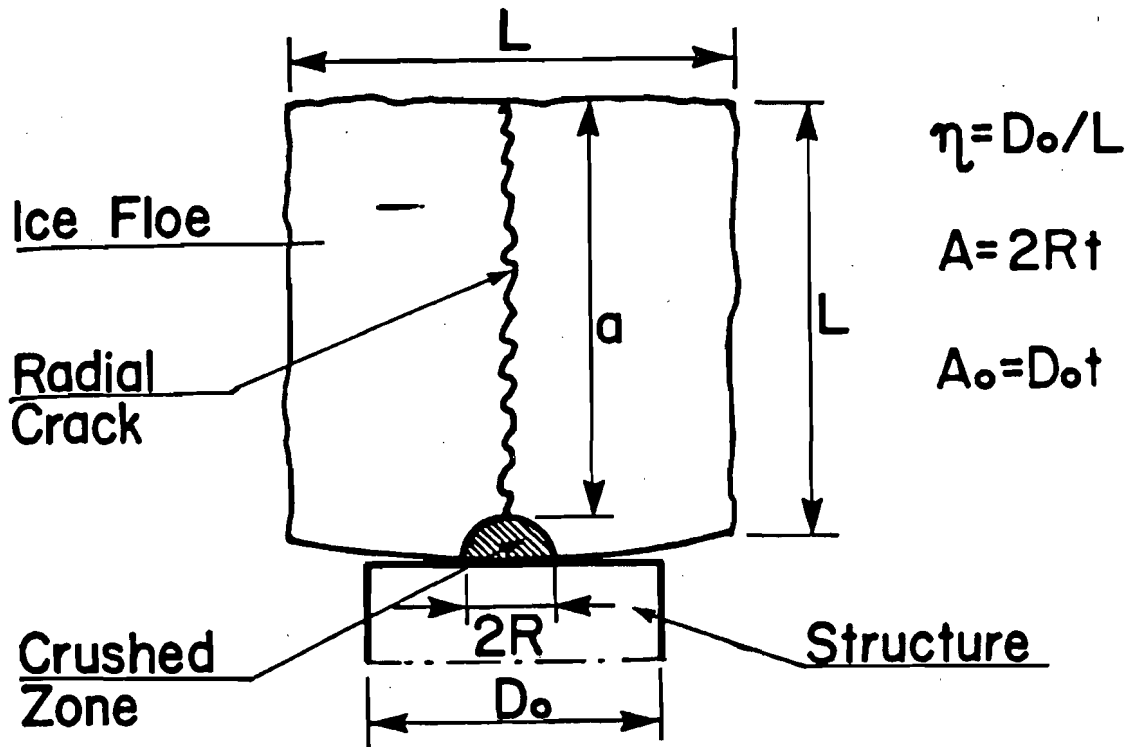


Figure 1. A conceptual model of splitting failure in large ice floes.

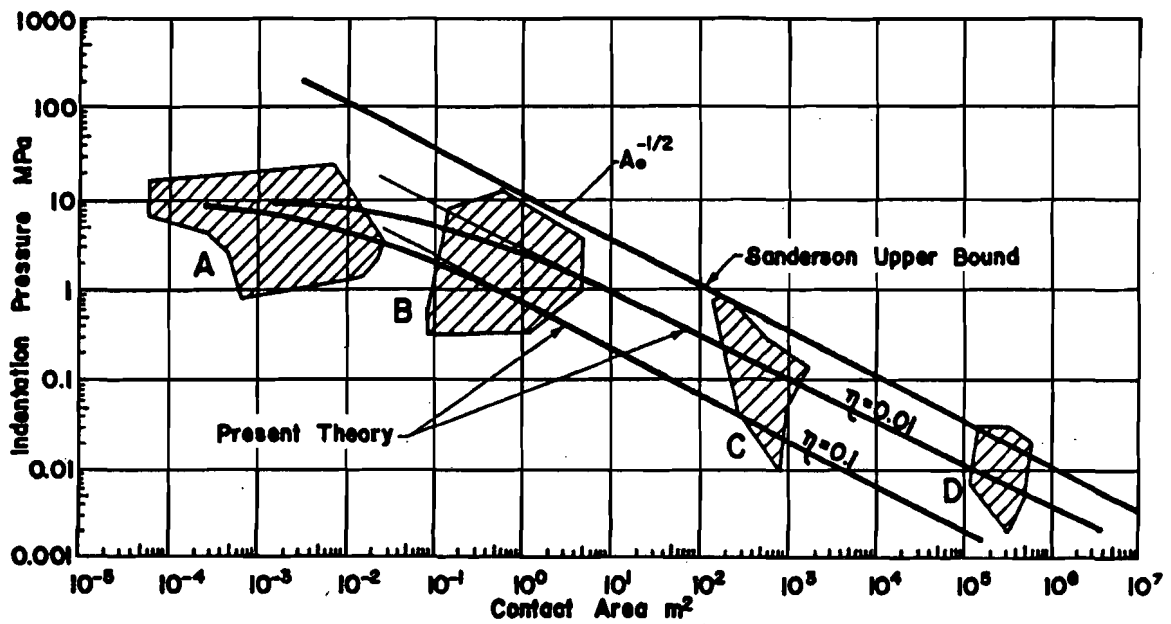


Figure 2. Correlation of predicted pressure-area curve with data collected by Sanderson (1986).

- The impact of finite size floes driven by their inertia. In the previous work, a semi-infinite ice sheet was considered, however, there is a marked difference in the far-field elastic stresses between those two solutions, so that there will also be a difference in the ice splitting forces or lengths of radial cracks.
- The compression of circular or square ice floe by two opposite forces or punches. The fracture mechanics approach gives quite different results from the plasticity approach considered, for example, by Reinicke and Ralston (1977). Some interesting results along these lines have really been obtained by Bhat (1988). The successful solution of this problem will provide a means for analyzing cushioning effects of small ice floes trapped between the structure and large floes.

In this short overview, only in-plane failure modes of ice such as radial cracking or splitting were discussed. The problem of indentation spalling and flexural cracking requires different analytical methods and will be addressed in future publications.

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# FULL-THICKNESS ICE STRENGTH MEASUREMENTS

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## INTRODUCTION

Full-thickness field tests of sea ice compressive strength were conducted by Exxon Production Research in the winters of 1979-80 and 1980-81. A companion program of small-scale laboratory tests was also conducted to provide a direct comparison with the field tests. The purpose of this work was to investigate the extent to which the compressive strength of natural sea ice depends on sample size.

Compressive strength is one of several material properties of sea ice that are of interest in the analysis of ice loads. Actual field geometry and natural loading processes are also critical. This test program was designed to investigate one of the parameters that are of interest in understanding natural ice loading events.

**Table 1. Natural ice loading parameters**

---

Geometry	Properties
Structure Shape	Compressive Strength
Contact Conditions	Bending Strength
Eccentric Loading	Shear Strength
Floe Size, Shape, Size Distribution	Fracture Toughness
Ridge Size, Shape, Consolidation	Elastic Modulus
	Viscous Flow
Processes	
Sustained Driving Motions	
Sustained Driving Forces	
Intermittent Driving Forces	
Isolated Floe Impact Loading	
Pack Ice Forces	

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## RESULTS

The results of the test program are illustrated in Figure 1, which compares full-thickness ice strengths that were measured in the field with those calculated from small-scale laboratory tests. These data do not indicate a significant scale effect.

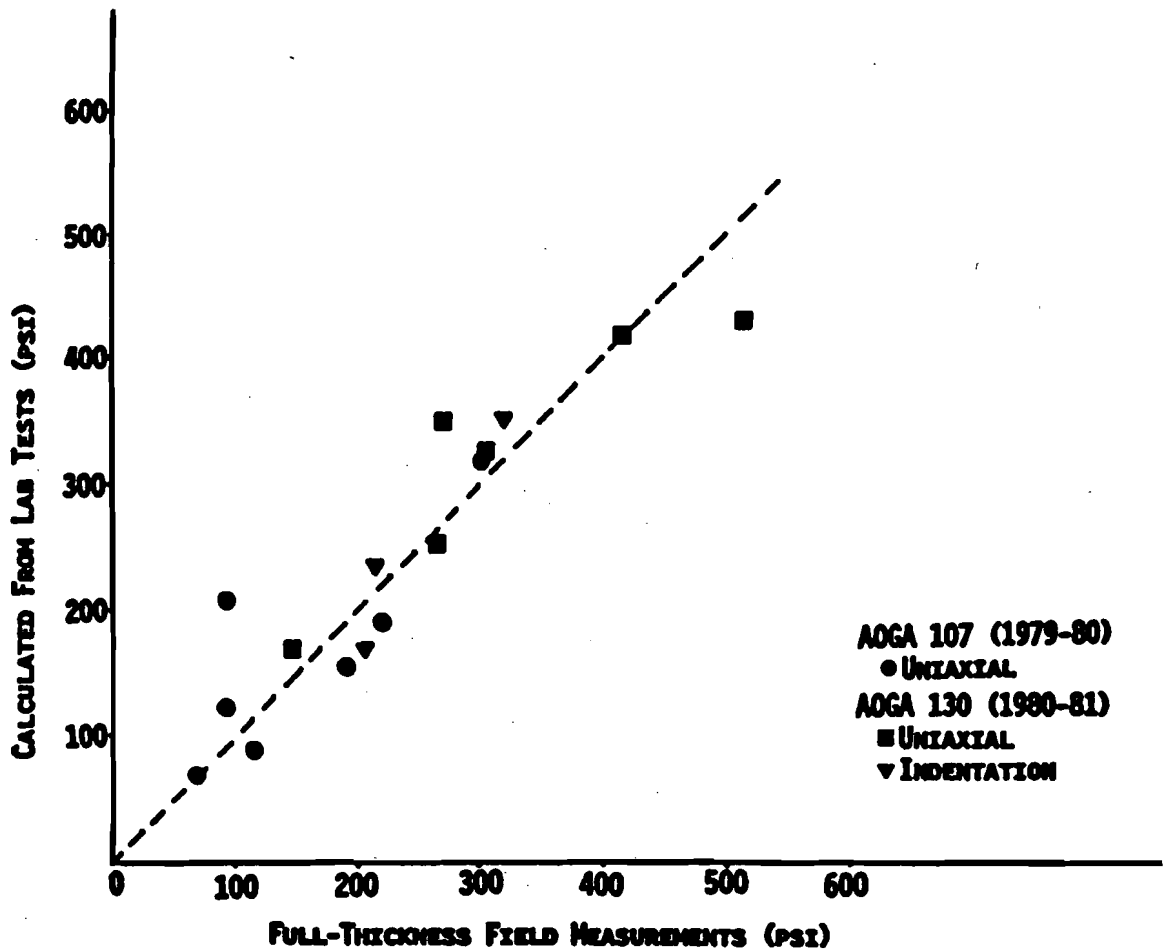


Figure 1. Comparison of ice strength calculated from laboratory and field measurements.

### CONCLUSIONS

The conclusions of the study can be summarized as follows:

- Field samples of sea ice were about 35,000 times larger than the laboratory samples; no "scale effect" was observed in the uniaxial compressive strengths.
- Field geometry and natural loading processes may be more important than ice properties for understanding natural ice loading processes.
- A non-uniform stress distribution is developed when a natural ice sheet is compressed uniformly ( i.e. there is no bending). The top half of the ice sheet transmits most of the load under these conditions.
- High ice strengths must develop quickly and can only last a short time. The highest ice strengths measured in the field tests occurred in tests that lasted only a few seconds.

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# ICE LOADS AND FAILURE MECHANISMS

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## INTRODUCTION

Since 1975, Canadian Marine Drilling, Ltd. (CANMAR) has been pursuing the question of the magnitude of ice loads. In the late 1970s and early 1980s, and in preparation for bottom-founded arctic structures, we used the best available theories and small-scale evidence to predict the loads. By 1984, however, after experience with the Tarsuit Island 1981/82, SSDC at Uriluk 1982/83, SSDC at Rogyuk 1983/84 and Hans Island 1983, we began to realize that we did not really understand the problem. Our measured loads were much lower than predicted. At first we thought that we had simply not been there long enough, but after the Hans Island 1983 tests, we realized that not only were we not seeing the loads, but we were not seeing the predicted failure mechanisms. At that stage we realized that we needed a radical reexamination of the phenomena in question.

One example is that theorists had predicted that the frozen-in to break-out condition would produce the highest loads. On the North Slope the minimal tide of 12 to 18 inches is sufficient to produce a complete ring of tidal cracks around every bottom-founded structure. The theoretical condition simply does not exist.

Another example is the problem of testing and scaling. If we send an ice party out to get cores, when the cores are drawn they tend to break into sections. (The samples are typically taken where the cores exhibit coherent isotropic properties.) These are then carefully returned to the laboratory for marking and uniaxial unconstrained compressive testing. The mean of this strength is then used as the base measure for global load estimates, but there are many problems associated with this approach. In the field the ice does not fail where the cores are strong but where they are weak, i.e. where they broke. The testing method bears little relation to real failure conditions. Finally, there is an absence of reliable scaling laws to take micro-ice properties to macro-ice loads. The scaling laws available to other engineering disciplines such as Reynolds, Froude and Mach are not appropriate in this area and to date their equivalents have not been found. It is therefore not surprising that the predictions were in error.

Since 1984 our approach has been twofold:

- If we need to predict ice loads, we rely on full-scale data together with suitable design and safety factors. Although we may not know exactly what phenomena are in the data sets, from observation we are confident that all the important phenomena are represented. We are much more comfortable replying on 1:1 scaling factors than 1:1,000,000.
- We have been looking at the way ice fails in the field in an attempt to understand the physics involved.

**FAILURE MECHANISMS**

Table 1 shows the principal failure mechanisms. Failures are divided into simultaneous and non-simultaneous groups, and there are two concepts associated with simultaneity:

- The phenomena should occur across the entire contact width at the same time, and
- The phenomena should be stable, meaning that it should occur for a reasonable time period.

Only crushing can be simultaneous as the other mechanisms are by their nature discontinuous.

**Table 1. Principal ice failure modes.**

Ice Failure Modes		
Simultaneous	Non-simultaneous	
Crushing	Crushing Bending Buckling Cracking Splitting Spalling & Flaking	Rafting Ridge Building & Rubble Forming Ride-up

**CONCLUSIONS**

The observed failures of ice sheets against wide structures appear to always be a combination of many failure mechanisms, regardless of location, time of year, ice type, thickness, temperature, interaction scenarios, etc. Wide can be defined as having an aspect ratio greater than 10.

Ice, like any material, will always fail by the mechanism requiring the least energy. This is most frequently buckling or bending, resulting in cracking and then ridge- or rubble-building. Buckling and bending takes place as a result of naturally-occurring asymmetries and irregularities in the ice such as crystal structure, temperature, thickness, etc. Artificial initiation is not necessary.

The conditions required for the classically described break-out after freeze-in do not occur in the field, since tide cracks and rubble discontinuities are present. These result in local buckling and bending, creep-type failures at very low strain rates instead of globally uniform compressive creep failure.

## THE FUTURE

We believe that future advances will be based largely on full-scale observations. There are a large number of analytical and engineering tools available, from finite and discrete element analysis to fracture mechanisms. Now that we have operated in the area for a number of years, the question is: "What phenomena actually occur and what are the most appropriate tools for the modeling and prediction of those phenomena?"

Specifically, we are interested in:

- **Crushing on slightly inclined structures:** The 6 degree angle of the sides of the Molipaq has shown instances of near simultaneous crushing at high aspect ratios. We would like to understand the contribution of the slope in the percentage of crushing.
- **Macro-characteristics of ice:** How does the anisotropic, flawed nature of ice affect the failure mechanism? A recent paper by T. Sanderson of British Petroleum gives a good initial overview.
- **Splitting:** We know splitting occurs and we know it limits the load, but we do not know how to predict it in the field. Griffith's critical crack length may be the route, but we need the macro-properties and macro-stress fields.



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**PAPERS ON  
SEA ICE  
MOTION & MECHANICS**

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# METEOROLOGICAL AND OCEANIC FORCING OF THE ALASKAN CONTINENTAL SHELF SEAS

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## INTRODUCTION

The Bering and Chukchi Seas are two large, shallow (<100 m), and smooth continental shelf regions connected by the Bering Strait. The Bering Strait, which is less than 60 m deep and has a cross-sectional area of  $4.1 \times 10^6 \text{ m}^2$ , provides the only avenue of exchange for heat, ice, water, and nutrients between the Pacific and Arctic Oceans. To the south of the Bering Strait, St. Lawrence Island forms two additional Straits, Anadyr to the west and Shpanberg to the east.

## GENERAL PATTERNS

The Bering and Chukchi Seas are seasonal ice zones, influenced by arctic, continental, and maritime air masses. In winter, arctic and continental weather elements predominate, with north to easterly winds, clear skies and a large diurnal temperature range. Moist maritime air is associated with two storm tracks, one parallel to the Aleutian Island chain and one curving northward into the Bering and Chukchi Seas. The southward advance of ice is controlled by wind-driven advection and cooling of the ambient water column to the freezing point. Since southerly winds, associated with northward propagating cyclones, inhibit ice advance, the seasonal ice extent is controlled primarily by an externally determined variation in storm track position due to large-scale differences in the general circulation.

Beyond 100 km from coastlines, ice drift is determined by the local force balance in response to wind stress at about 3% of the wind speed. Ice drift in the northern Bering-southern Chukchi Seas is influenced by a general northward flow of water driven by higher sea level in the Pacific. Approximately 80% of the ocean transport is through Anadyr Strait. This pattern is reversed or augmented by wind driven coastal currents resulting in ice drift through Bering Strait with speeds as much as 15% of the local wind speed. Little is known about ice drift in the Gulf of Anadyr to the far west or the influence of ice strength in inhibiting coastal currents in the Chukchi Sea.

The Beaufort Sea is on the order of 50 km wide. It is influenced by an offshore, westward-setting current, an eastward-setting undercurrent originating in Barrow Canyon, and an inshore, predominately westward-setting, wind-driven current which is modified by the passage of storms. In summer the extent of ice in the Beaufort Sea is controlled by the amount of sunlight received during the same summer season.

## FORECASTING SEA ICE

Short-range or "nowcasting" sea ice forecasts will be greatly enhanced in 1990 with the launch of a Sidelooking Airborne Radar (SAR) on the ERS-1 satellite. Extended ice

forecasts of two to five days are becoming feasible, but require a fully coupled ice-ocean model for the Alaskan continental shelves.

The predictability of the extent of summertime ice in the Beaufort Sea has been investigated with observational data (Rogers 1978) and most recently by ice-model-generated ice thickness fields (Ross 1984). Based on 20 years of simulations, Ross shows that large changes in July and August ice thickness from year to year are often unpredictable solely on the basis of ice thickness data from the previous season. This finding is demonstrated by the tendency for August thickness to correlate much more strongly with July thickness anomalies than with May thickness anomalies. These results support the conclusion of Rogers (1978) that temperature and wind direction become progressively more important throughout the summer in affecting ice conditions in the Beaufort Sea. The optimal approach to summer ice predictability is to use projections of atmospheric anomalies in conjunction with the sea ice model.

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# SEA ICE CHARACTERISTICS, MOTION AND INTERACTIONS

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## INTRODUCTION

The determination of ice loads on structures involves large-scale forces from winds and ocean currents as well as ice failure mechanisms and strength.

### ICE LOADS ON STRUCTURES

Figures 1 and 2 show how a structure fits into the sea-ice environment. Figure 1 is a large-scale view of sea ice (pack ice) loaded by winds and ocean currents. These environmental driving forces are what ultimately cause loads on structures. Large-scale driving stresses and displacements of pack ice can be determined by modeling. The large-scale ice forces or displacements, which might have been determined from a large-scale ice dynamics model, are shown on the boundaries of Figure 2. Various structures and ice types are shown. In the center of the figure, a structure is indicated which might be a gravel island, drill ship, conical structure, etc. Also, a submerged wellhead and pipeline are indicated. Figure 2 also shows a road over the ice which has been constructed through a ridge and has been interrupted by a lead. The ice types shown in Figure 2 include an ice island, a ridge, a region of fragmented ice cover, and a rubble field. In addition, there is a ridge which is being built, an area where rubble is being formed, and a crack meandering through the icescape. The ridge-building, rubble-building, and lead represent areas where sea ice is interacting with itself and thus limit the amount of force that can be transmitted through the sea ice cover.

### ICE STRENGTH

The strength of sea ice can vary enormously and on variety of scales. In sea ice sheets the strength depends upon temperature, brine volume, crystal orientation, and strain rate. In rubble fields, the internal friction and cohesion control the strength, however, cohesion depends on the consolidation of the rubble field which changes during the life of the rubble field. In a completely consolidated rubble field, the strength could approach that of a ridge. For the fragmented ice cover, strength depends on minimum block size; in the plastic representation for pack ice, strength depends on the thickness distribution, but most heavily on the distribution of thin ice such as that in leads. With the strength of the ice types depending on such diverse variables, it is clear that one cannot specify fixed ratios for their strength.

### ICE LOADS

A procedure for determining sea ice loads could consist of finding ice forces due to all possible ice interaction mechanisms, and using the largest resulting load as the design load. Figure 3 is a flow chart showing the information required to obtain these ice load criteria.

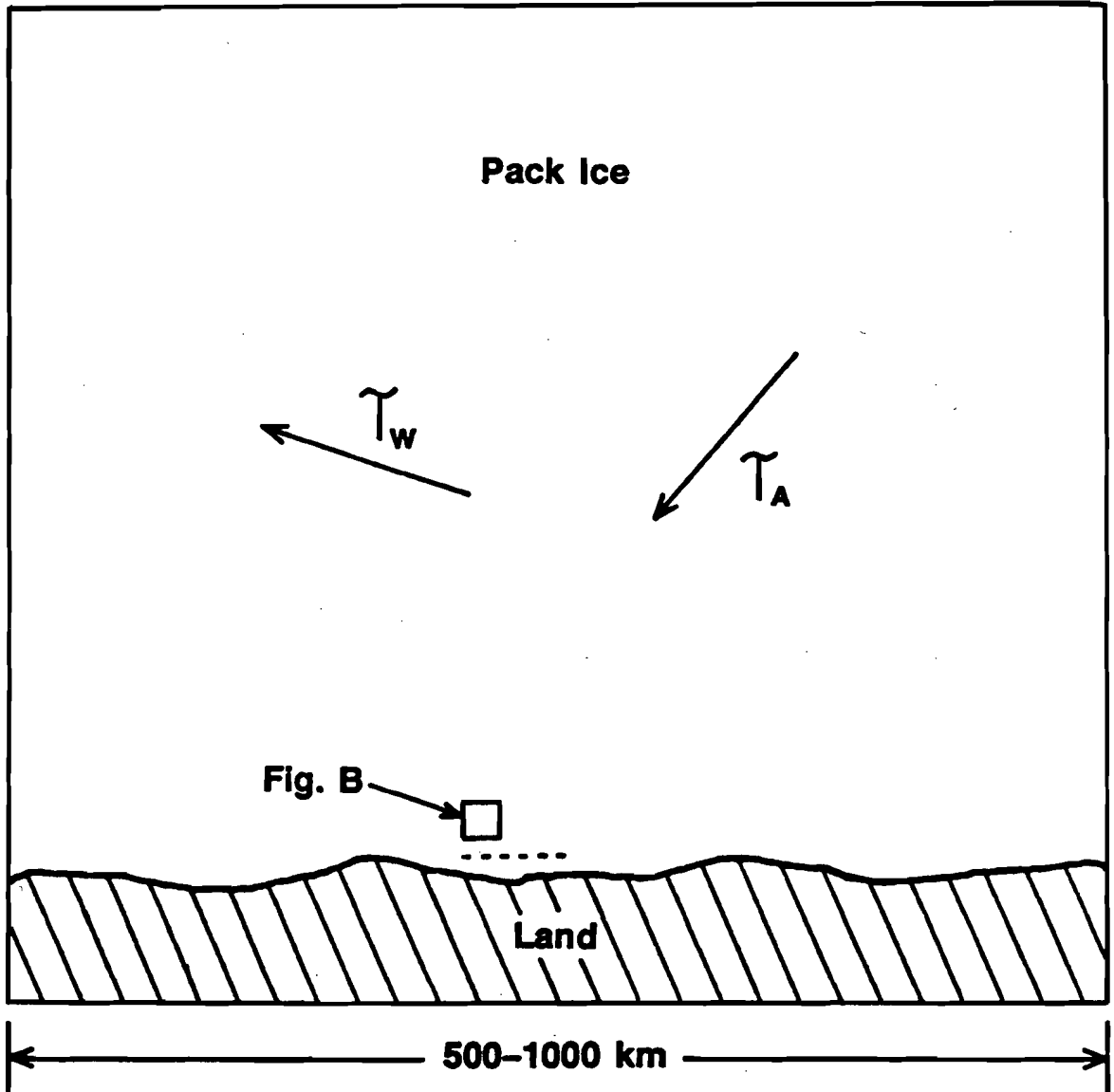


Figure 1. Loading forces on pack ice.

Cell 1 indicates the types of structures that might be considered and Cell 2 shows the ice features. For a given structure and ice type, the corresponding interaction forces are considered in Cell 3; ice properties from Cells 4 and 5 are required for this purpose. The loads calculated from Cell 3 are caused by environmental driving forces shown in Cell 6, and these are brought together in Cell 7, leading to the ice load criteria of Cell 8. These must be augmented by special criteria in Cell 9.

### Force or Displacement

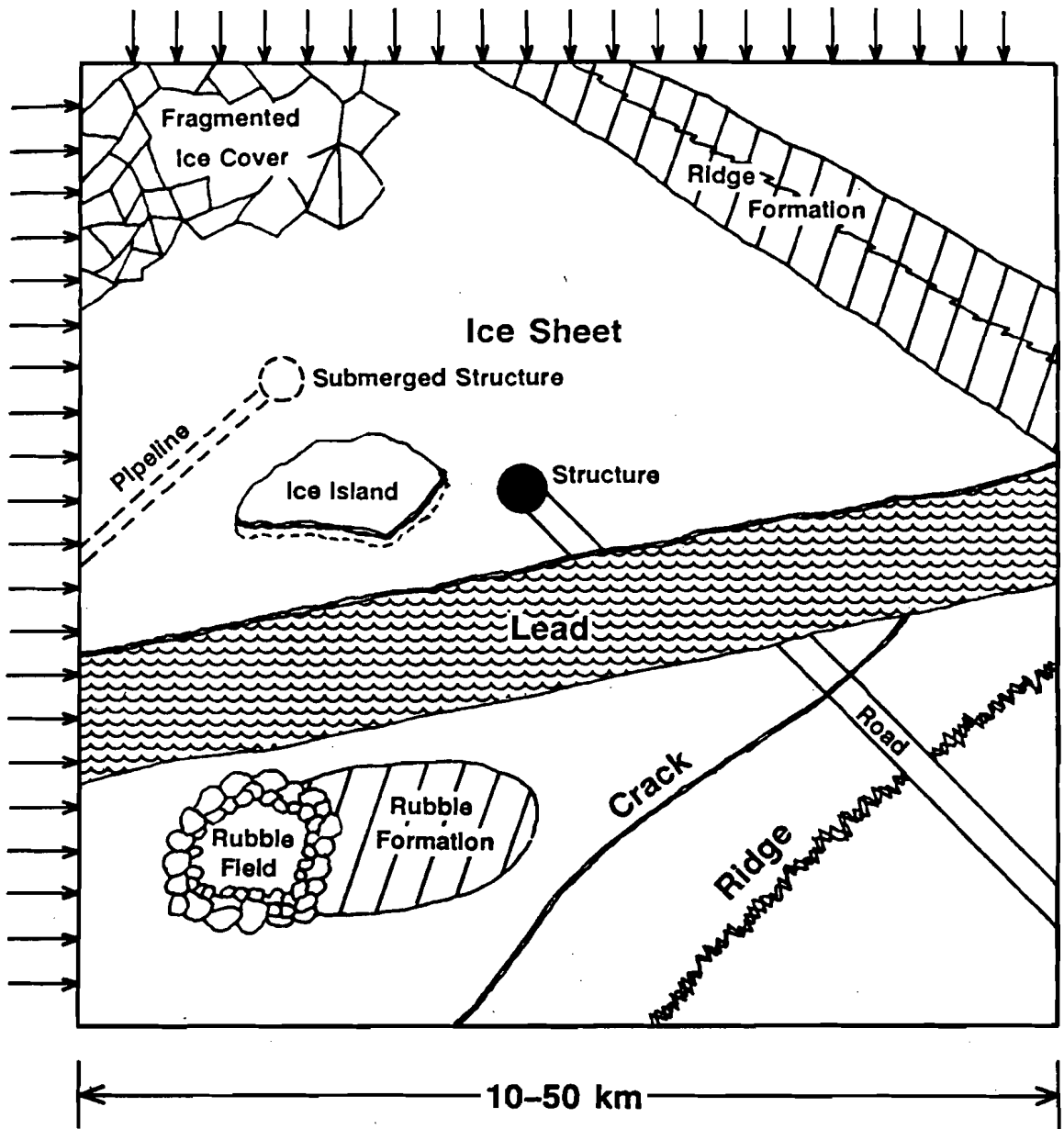


Figure 2. Schematic of typical forces, structures and ice types under consideration.



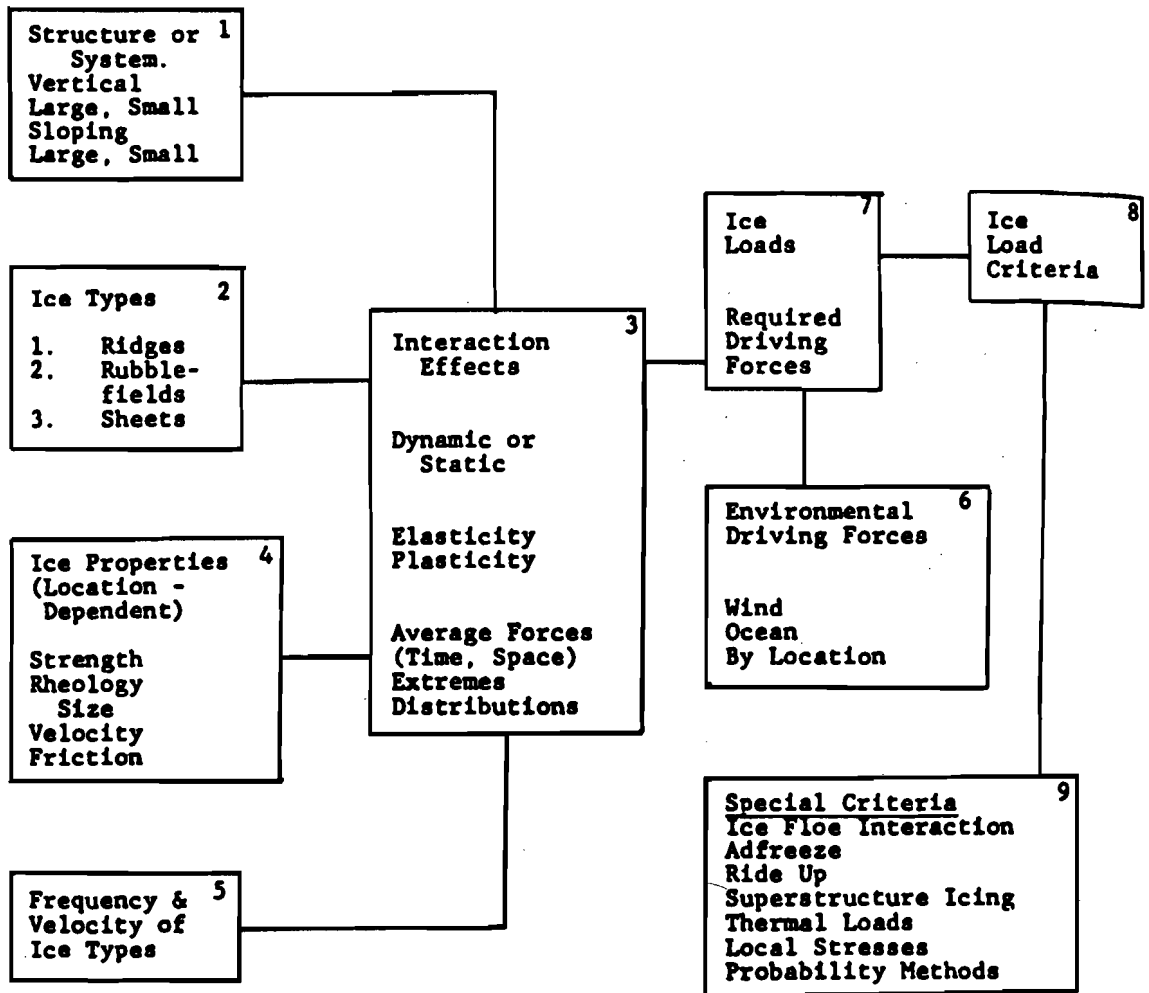


Figure 3. Flow chart for ice load criteria.

## RESULTS OF THE ARCTIC BUOY PROGRAM

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### INTRODUCTION

The Arctic Data Buoy Program has been monitoring sea ice motion, surface atmospheric pressure and temperature over much of the Arctic Ocean since 1979. An array of 10 to 20 drifting buoys is maintained on the sea ice, with a spacing of roughly 500 km (Figures 1 and 2). The program is described in detail by Untersteiner and Thorndike (1982). The buoy data serve two purposes:

- Establishment of a research data base for studies of air-sea-ice processes, from which climatological statistics on ice motion, pressure and wind may be estimated, and
- Provision of near-real-time, synoptic data for analysis and forecasts, on time scales of 1 to 3 days, in support of offshore and coastal operations.

### RESULTS

Using the data for geophysical and climatological research, scientists at Polar Science Center (PSC) have studied sea ice kinematics (Thorndike 1986, Colony and Thorndike 1984, Colony and Thorndike 1985, Colony 1986), synoptic pressure fields (Thorndike 1982), wind- and current-driven ice motion (Thorndike and Colony 1982, Moritz and Colony 1988), and 1 to 3 day wind forecasts (Moritz 1983). A summary of these studies follows.

The daily average sea ice velocity at any location, denoted by  $\underline{u}$ , is viewed as the sum of two parts:

- A steady, long-term mean velocity  $\bar{\underline{u}}$  that defines the general circulation of the ice, and
- Deviations  $\underline{u}'$  of any particular daily value from  $\underline{u}$ .

The  $\bar{\underline{u}}$  field, Figure 3, estimated from all available drifting stations and buoys, exhibits an anticyclonic gyre centered in the northern Beaufort Sea, and a broad, streaming motion from the Soviet Arctic through Fram Strait. The magnitude of  $\bar{\underline{u}}$  varies spatially from about 1 to 4 cm/sec, excluding the marginal seas. In the central basin, the deviations ( $\underline{u}'$ ) are well-approximated by a homogeneous, isotropic, Gaussian random process with a variance of about  $(8 \text{ cm/sec})^2$ , an autocorrelation time scale of about 3 days, and an autocorrelation space scale of about 800 km. The rotational part of the velocity fields  $\bar{\underline{u}}$  and  $\underline{u}'$  is one order of magnitude larger than the divergent part, making the latter difficult to estimate, due to interpolation errors.

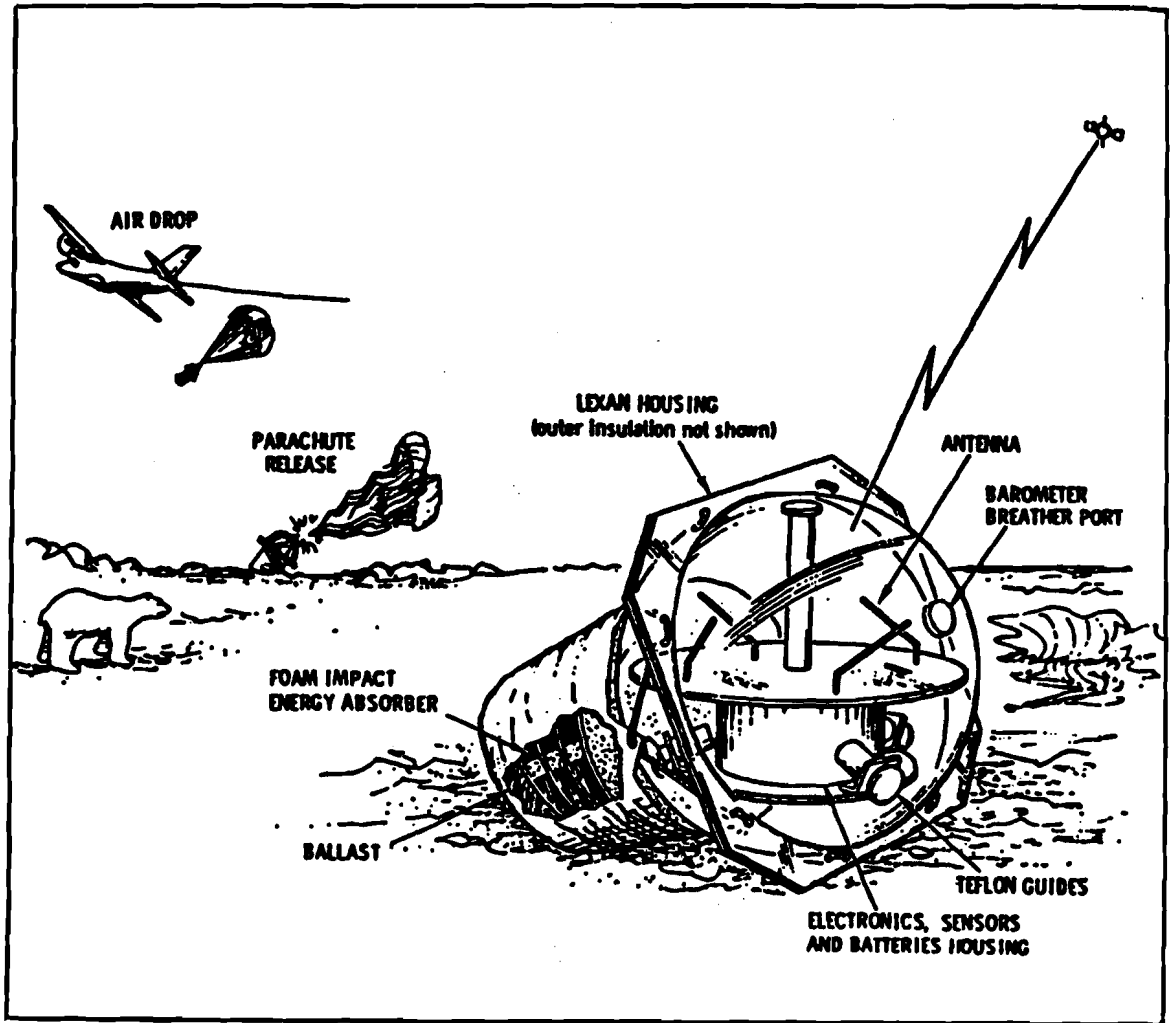


Figure 1. Schematic of air-deployable random access measurement system (Brown and Kerut 1978).

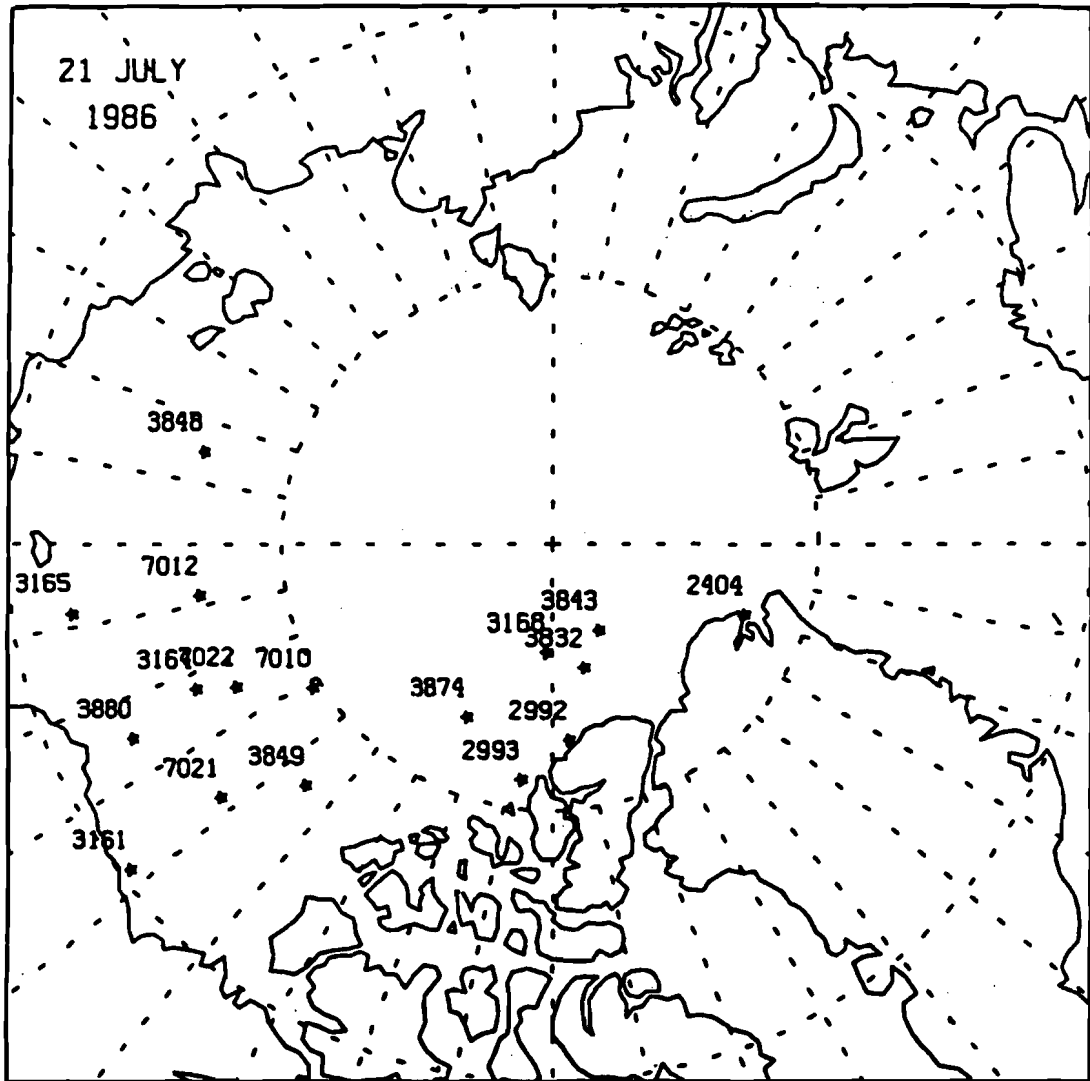
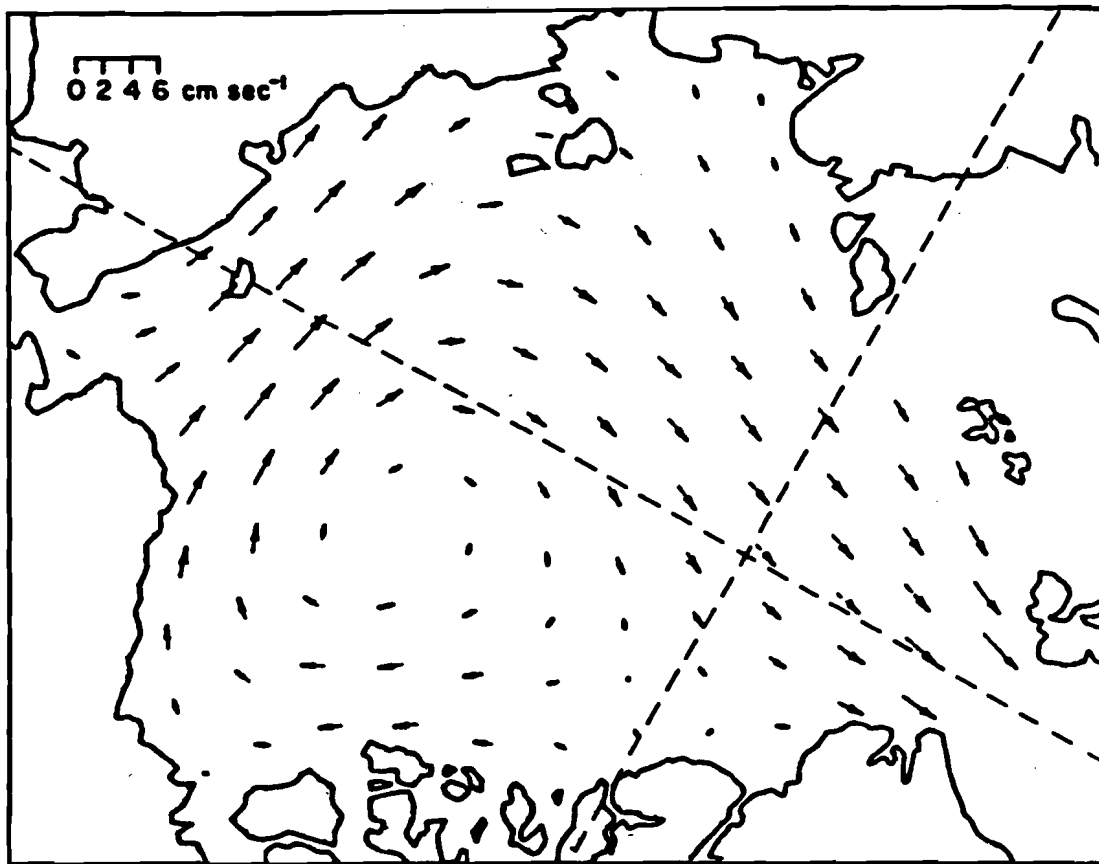


Figure 2. Locations of arctic data buoys on 21 July 1986.



**Figure 3. Estimated mean annual sea ice velocity field  
(Colony and Thorndike 1984).**

The sea level pressure field may be partitioned in the same way as the ice velocity:

$$p = \bar{p} + p'$$

The 5-year mean annual  $\bar{p}$  field is dominated by a high pressure cell over the Beaufort and East Siberian Seas, from which a ridge extends towards the northeast Greenland coast, Figure 4. The geostrophic wind

$$\underline{G} = \underline{k} \times \text{grad } (P) / \rho f$$

associated with the mean pressure field varies spatially from about 1 to 4 m/sec in magnitude. The deviations ( $\underline{G}'$ ) are again well-described by a homogeneous, isotropic, Gaussian model, with variance  $(8 \text{ m/sec})^2$  and autocorrelation scales of 2 to 3 days and 1200 km.

A simple model for sea ice velocity is:

$$\underline{u} - \underline{u}' = \underline{A} (\underline{G} - \underline{G}') + \underline{c} + \underline{e}$$

Fitted to the local ice motion and winds at the buoy locations this entails a drift factor (matrix)  $\underline{A}$  that rotates the wind vector 8 degrees to the right while reducing it by a factor of 100. The fitted constant  $\underline{c}$  is interpreted as a mean surface geostrophic ocean current and  $\underline{e}$  is the residual error of the linear model. Typically, 70% of the variance of  $\underline{u}'$  is accounted for by wind driving. The long term mean motion is about 50% due to  $\underline{A}\underline{G}$ , and 50% due to  $\underline{c}$ . This equation performs less well near coasts (within 200 km of shore) due to the growing importance of ice stress and coastal currents, which alter  $\underline{A}$  and increase the variance of  $\underline{e}$  (Figures 5 and 6).

The mean field  $\underline{u}$  and a Markovian model for the 90-day average deviations from  $\underline{u}$ , may be used to estimate the probabilities of different sea ice trajectories for analysis of occurrences such as oil spills or ice island paths (Colony and Thorndike 1985, Colony 1986) independent of assumptions about poorly-known mechanical properties of sea ice or large scales (Figure 7).

The National Meteorological Center (NMC) produces daily forecasts of the sea level pressure for lags of 24, 48, and 72 hours. Moritz (1983) found root mean square forecast errors of 4 m/sec, 5.2 m/sec and 6.2 m/sec by comparing the NMC predicted  $\underline{G}$  to the values measured by the buoy array. Therefore the NMC forecasts provide useful information on future ice motions over 1 to 3 day periods (Figure 8).

## CONCLUSIONS

Most of the conclusions cited previously apply to the central Arctic ice pack. As more data accumulate in the nearshore (<200 km) environment, additional studies should be made to determine the effects of ice stress, coastal wind and currents on ice motion. Present plans call for maintaining a buoy array through 1990 at least. With such a 10 to 15 year data base, the low frequency (interseasonal, interannual) variability of pressure and ice motion can be assessed.

Sea Ice Forces and Mechanics

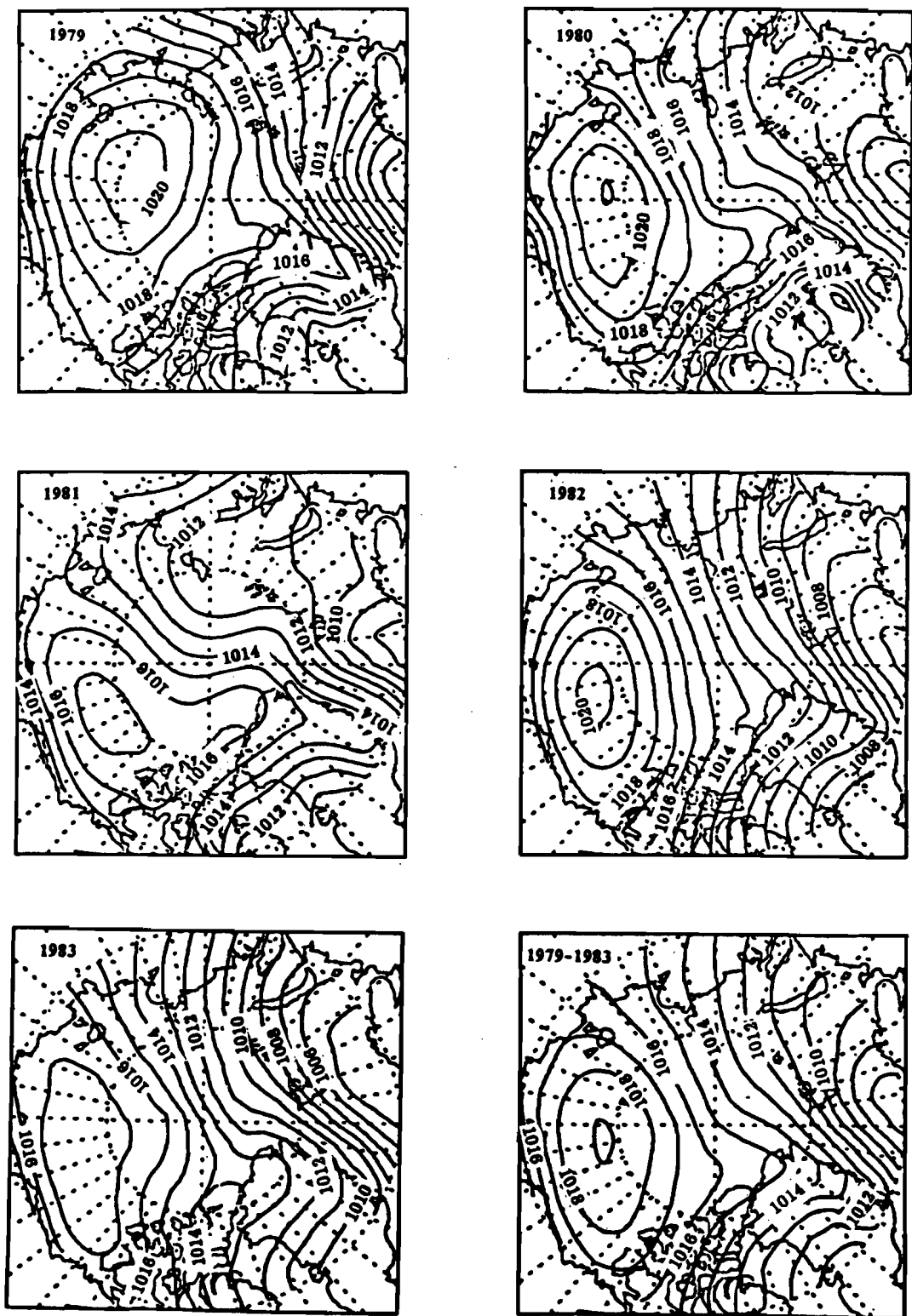


Figure 4. Mean annual sea level pressure field, 1979-1983.

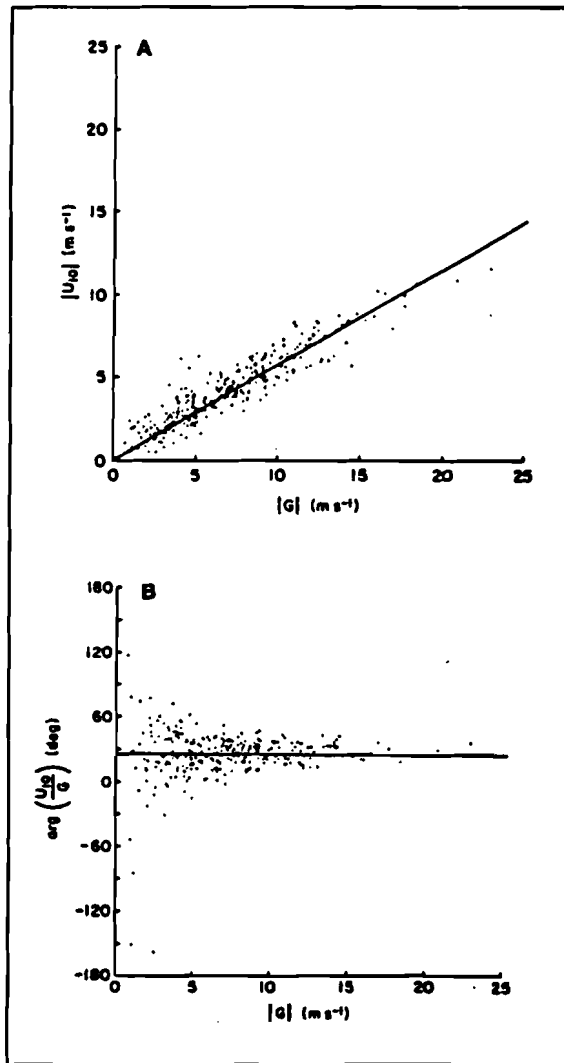


Figure 5. Comparison of daily average 10 m wind measurements  $U_{10}$  daily average geostrophic wind estimates at AIDJEX Camp Caribou in the Beaufort Sea, April 1978-April 1976 (Albright 1980): a)  $U_{10}$  magnitude, and b) boundary layer turning angle plotted against geostrophic speed.

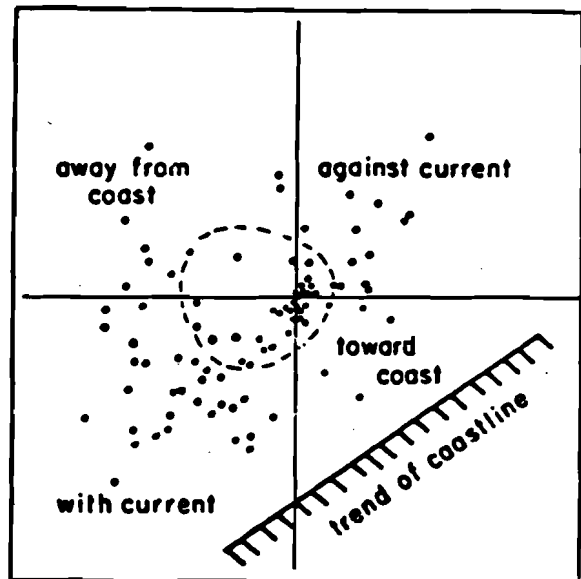


Figure 6. At buoy 1919, close to the Canadian Archipelago, the ratio  $U/G$  versus wind direction, showing greater ice response for offshore than for onshore winds "ratio" (second and fourth quadrant). The response is also larger when the wind is parallel to the mean current (third quadrant) than opposed to it (first quadrant).



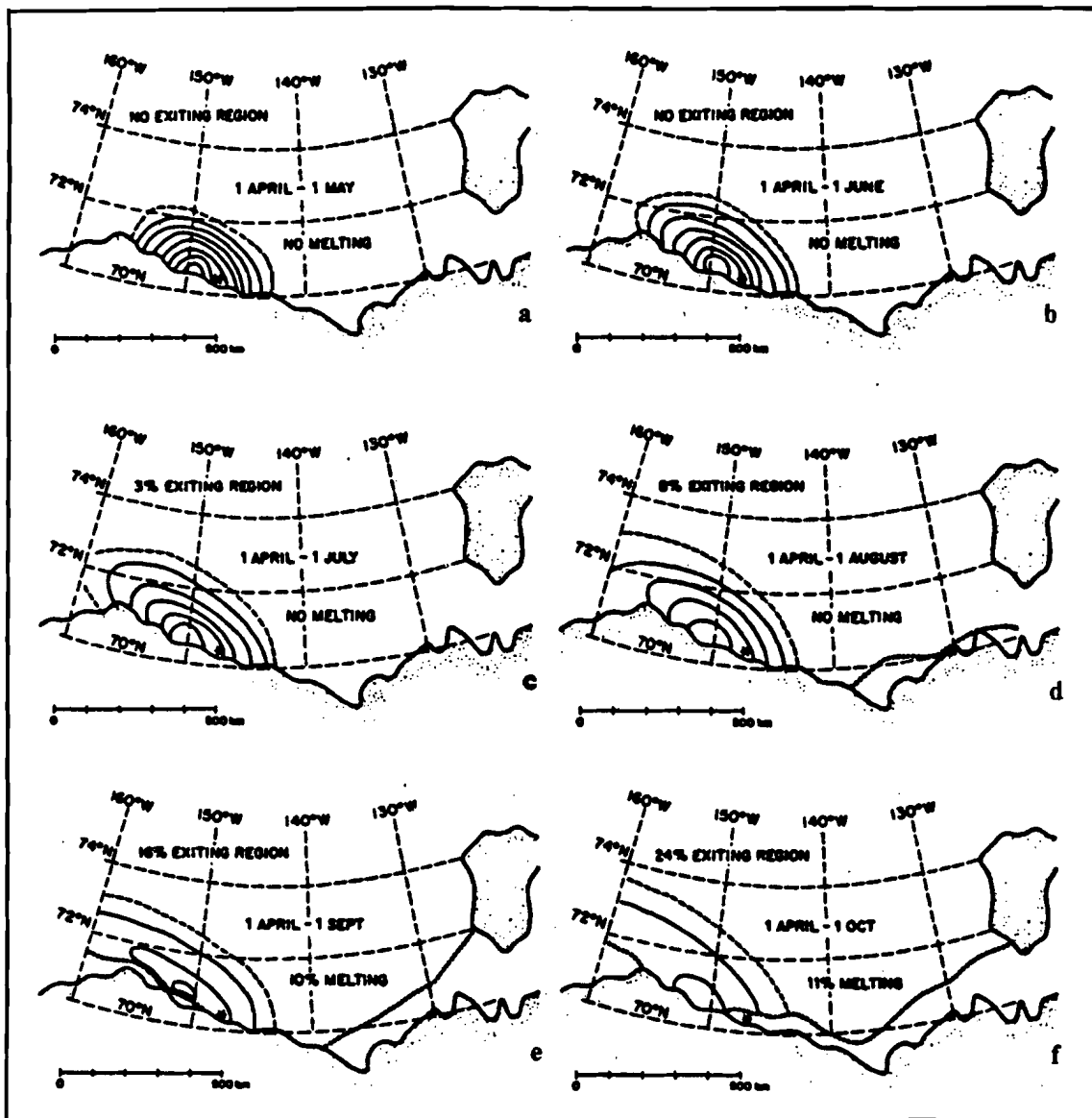


Figure 7. Probability density function for the position of oil spilled in Prudhoe Bay on April 1 for: a) May 1, b) June 1, c) July 1, d) August 1, e) September 1, and f) October 1.

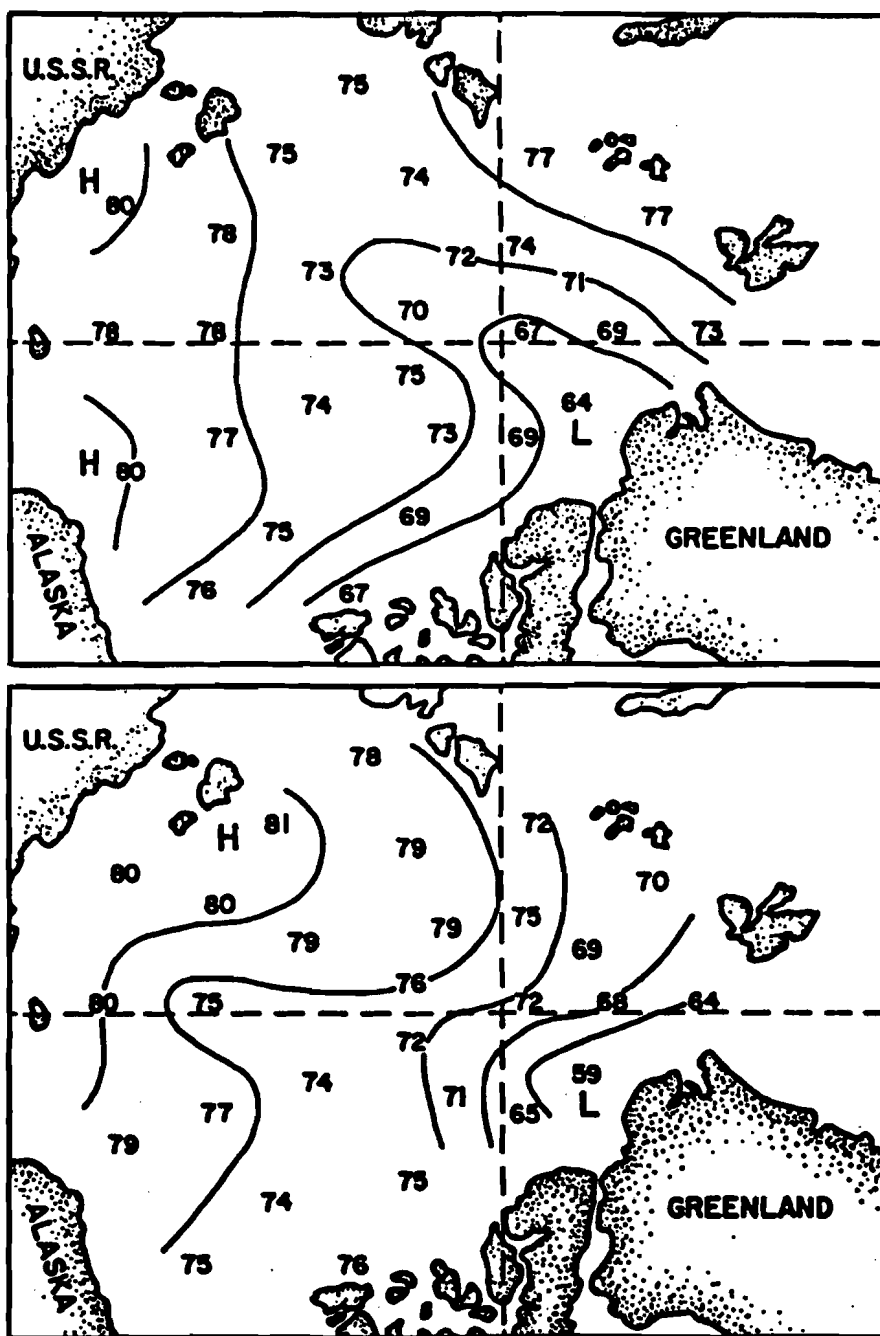


Figure 8. Grid point estimates of squared correlation between NMC 24-hour forecast geostrophic wind and observational analysis: a) March-December 1979, and b) May-December 1980.

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# ICE STRESS MEASUREMENTS AROUND OFFSHORE STRUCTURES

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## INTRODUCTION

The magnitude of ice forces on offshore structures can be estimated from analytical models, model tests, and field measurements. Analytical models and model tests provide upper bound ice load estimates, as conservative assumptions are made to compensate for a lack of understanding of the large scale mechanical properties of ice covers. Field measurements of ice stress are needed to obtain actual ice loads on structures for comparison to the analytical models and model test results. The field measurements can also be used to determine the stress distribution in the ice sheet and the large scale mechanical properties of the ice cover.

## METHODS

The U. S. Army Cold Regions Research & Engineering Laboratory (CRREL) has conducted field measurement studies of the ice stress around two offshore structures using biaxially sensitive stress sensors. The sensor consists of a stiff steel cylinder 20.3 cm long and 5.7 cm in diameter, and with a wall thickness of 1.6 cm. The ends of the sensor are threaded to accommodate a rounded end cap on the lower end. Extension rods can be screwed to the top of the sensor to position the sensing portion of the gauge at any desired depth in the ice sheet.

Principal ice stresses normal to the axis of the sensor are determined by measuring the radial deformation of the cylinder wall in three directions. This is done by measuring the diametral deformation of three tensioned wires set at 120 degrees from each other across the cylinder diameter.

## RESULTS

Test evaluations of the stress sensor indicate that the sensor responds immediately to applied loads and can resolve biaxial stresses to within 10% of the applied stress. The sensor can resolve stresses to about 20 kPA (3 lbf/in.<sup>2</sup>) when it is imbedded in ice.

The first field study was conducted during the spring of 1984 around ESSO's caisson-retained island (CRI) Kadluk. The CRI was located on a man-made berm in 14 m of water in MacKenzie Bay, NWT, Canada. Ice movement which occurred during deployment left the CRI at the end of a peninsula of ice. Eighteen biaxial ice stress sensors were deployed at six sites on the south side of the structure-ice rubble complex. The sensors provided information on the vertical and lateral stress distribution in the ice sheet. Ice load on the structure-ice rubble complex was calculated from the stress measurements.

The stress measurements from one of the six sites are shown in Figure 1. The principal stresses are P and Q (positive value for compression) and theta is the angle measured counterclockwise from the primary principal stress direction P to magnetic

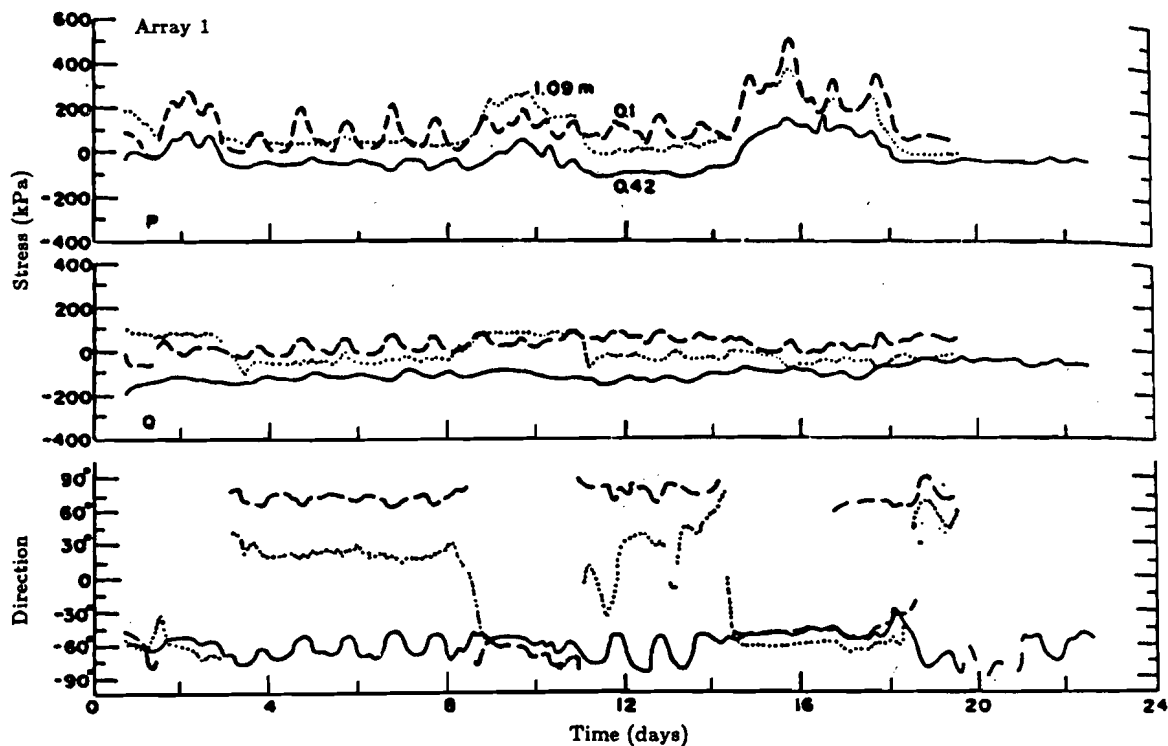


Figure 1. Vertical variation of ice stress at Site 1 during the latter part of March. Day 0 corresponds to March 12.

north. The ice was 1.7 m thick at this site and sensors were placed at depths of 0.10, 0.42 and 1.09 m to provide a vertical stress profile. It is evident that the vertical stress distribution can be complex. Contrary to our expectations, maximum stresses were not observed only in the top part of the ice sheet, but also in the middle and bottom of the ice sheet at different times. During significant stress events [ $>100$  kPa ( $>15$  lbf/in.<sup>2</sup>)] the principal stress directions tended to be aligned in the top, middle and bottom of the ice sheet. During periods of low stress [ $<100$  kPa ( $<15$  lbf/in.<sup>2</sup>)] the stress directions varied considerably with depth; stress at all depths varied in a cyclic manner in response to diurnal fluctuations in the air and ice temperatures.

The maximum compressive stress measured was about 500 kPa (75 lbf/in.<sup>2</sup>). This was in the top portion of the ice sheet at Site 1 on 27 March. The corresponding average full thickness ice stress was 300 kPa (44 lbf/in.<sup>2</sup>). Tensile stresses were always lower than 140 kPa (20 lbf/in.<sup>2</sup>) and may be a measure of the large-scale tensile strength of the ice cover.

The complexity of the vertical stress distribution suggests that the ice sheet was in a state of bending, and that superimposed on the bending stresses were local thermal stresses. This is probably reasonable in that upward and downward bending of the ice sheet was evident along the rubble pile in front of the structure. Flexure failure of the

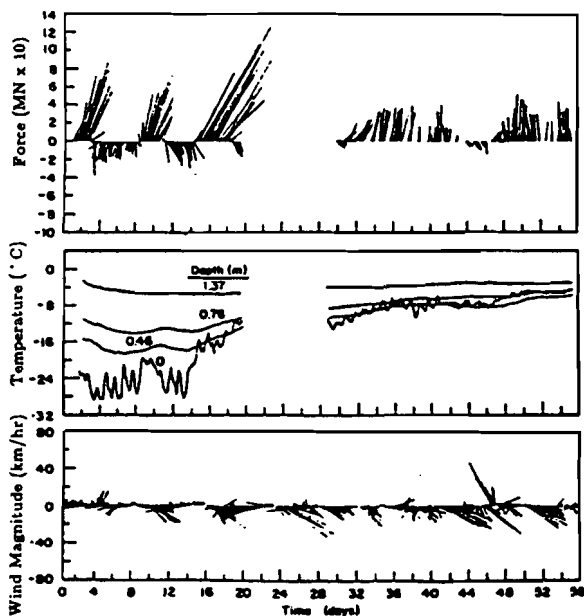


Figure 2. Ice forces, ice temperature, and wind data at the CRI ice island-rubble complex.

May 1985. Mukluk is located in 15.2 m of water in Harrison Bay, Alaska. Stress sensors were deployed at seven sites around the island. Stresses were measured and stored on-site using battery powered data loggers set on the ice.

There were no major storms during the study and the average stresses measured in the 2 m thick ice were small, usually less than 100 kPa (15 lbf/in.<sup>2</sup>) and always less than 200 kPa (30 lbf/in.<sup>2</sup>). The measured stresses were primarily due to thermal ice pressures as can be seen by the correlation between ice sheet temperature rise and stresses at site 6 (Figures 3 and 4).

The studies at Kadluk and Mukluk islands were both conducted in landfast ice areas and were initiated in March, after the ice sheet had stabilized. No significant storms occurred while stress measurements were being made during either study and stresses were always less than 500 kPa (75 lbf/in.<sup>2</sup>). Ice rubble was being formed continuously during the Kadluk study and low stress measurements may have been because the ice was failing in flexure. Low stress measurements at Mukluk were due to the lack of significant storms or ice movement. Thermal stresses at Mukluk were lower than at Kadluk, perhaps due to the lower yield stress of saline ice in Harrison Bay as compared to the relatively fresh water of MacKenzie Bay. In addition, the rate of temperature increase in the ice was lower around Mukluk than near Kadluk.

ice sheet at the rubble pile would also explain the relatively low ice stress values which were measured.

The total load acting on the CRI was calculated from the average normal and shear stress measurements at Sites 1, 2, 3 and 4. The results are shown in Figure 2 along with the ice temperature and wind data acquired during the study. The force vectors point in the direction of the applied load and the wind vectors point in the direction into which the wind was blowing. The maximum load calculated was 150 MN (16.8 tons). Ice load, ice temperature, and wind data indicate that all significant ice stresses were of thermal origin. The stresses are produced by the seaward motion of the ice as a result of the expansion of the ice sheet between the structure and the coastline.

The second field stress measurement study was conducted around SOHIO's gravel island Mukluk from March through

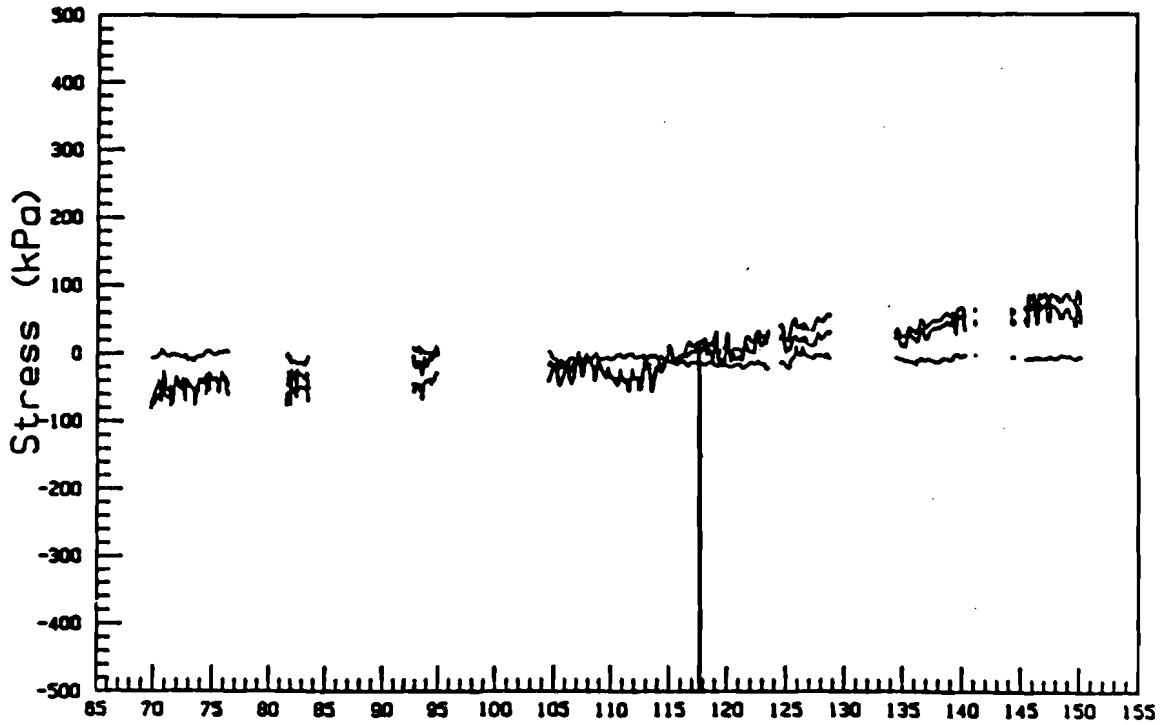


Figure 3. Average stress components at Site 6, Mukluk.

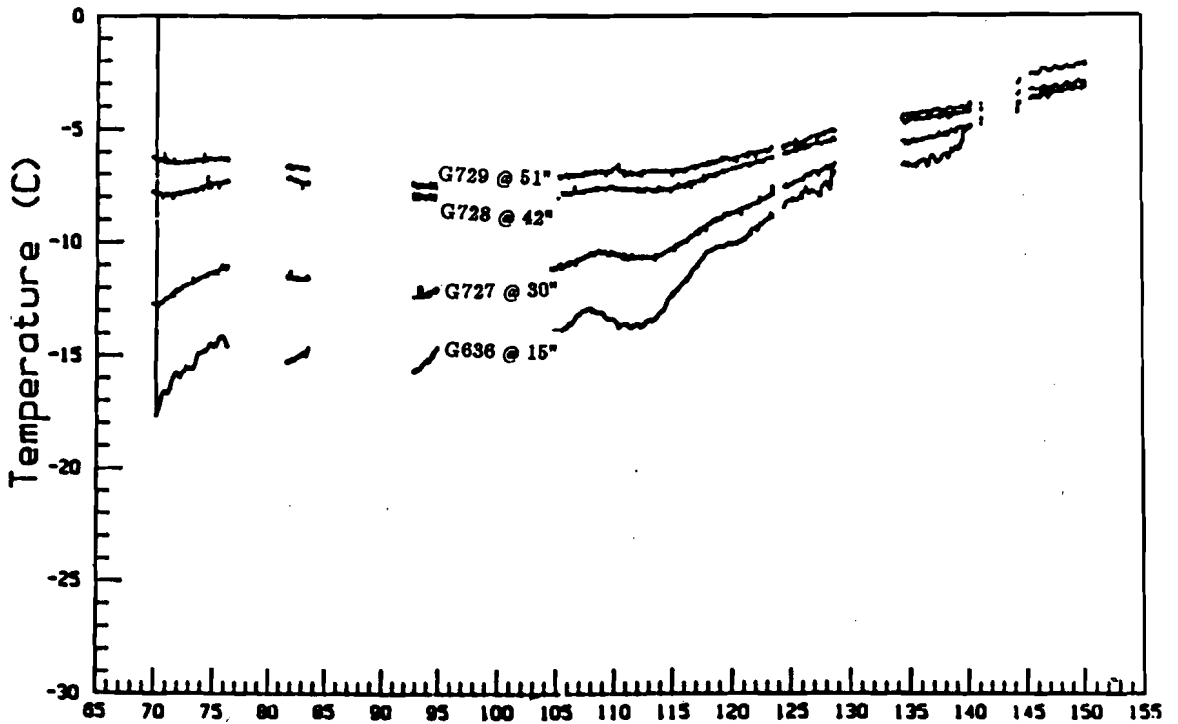


Figure 4. Ice sheet temperature rise at Site 6, Mukluk.

## CONCLUSIONS

Our measurement programs have not measured design ice loads for structures, but we do have a better understanding of the distribution of stress through an ice cover. This information is useful when formulating prediction models. Stress measurements during major storms and in more dynamic ice conditions are needed to better define expected peak loads. It is anticipated that significantly larger stresses and loads will be observed early in the winter when the landfast ice is more dynamic. This will require that stress measurement data be telemetered from the stress sensors since data transmission through wires is often impossible during the ice movement which accompanies major storms. We are currently in the process of developing the capability to install stress sensors in an ice cover and telemeter the data to a central acquisition point. This will allow us to make more reliable stress measurements during dynamic ice movement events.

Conducting ice stress measurements in the field is difficult, time consuming and expensive. It is necessary, however, to obtain actual ice stress and ice loads on structures for input and verification of ice-force prediction models.



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# TOTAL ICE FORCE MEASUREMENTS ON AN INSTRUMENTED STRUCTURE, AN OVERVIEW OF ICE ISLANDS, AND SPRAY ICE BONDING TO OFFSHORE STRUCTURE COATINGS

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## DRIFTING ICE ISLANDS

Drifting ice islands are a severe hazard in the Beaufort Sea. Over 25 such islands are passing along the coast of the Canadian archipelago and are expected to reach the Alaskan coast in the next three years. Ranging in size up to 9 kms across and 42 m thick, they originate by calving from the Ward Hunt Ice Shelf. Three types of trajectories have been identified. Possible calving of ice islands in the future is also mentioned.

Ice islands are produced in the Ellsmere ice shelf area. Most often, they move southwest along the coast, continuing around the Beaufort gyre. Some complete another circuit in the gyre, while others leave the Arctic Ocean and enter the North Atlantic.

The cluster of ice islands now being studied is at 80°N, 106°W, north of Ellef Ringnes Island. Salinities of ice island ice are zero or nearly zero. Crystal sizes are large. In some part of the Ward Hunt ice shelf, there is saline ice on the bottom and fresh ice in the upper parts. In the largest ice island, which came from the east side of the Ward Hunt ice shelf, the salinities are very low. At the same time, there are high values of tritium in the bottom ice, which indicates that the ice from this zone was accreted since 1952.

The Canadian Polar Continental Shelf Project deployed a Polar Science Center buoy on the largest ice island in 1983. The data helped to categorize the trajectories of drifting ice islands. The trajectory is generally parallel to the coast of Ellsmere Island, and there are three different kinds of movements. Large daily movement events occur only two or three times a year, during which there might be 10 km or more of movement. Such large movements are in the southwesterly direction; there are also back-and-forth movements, 1-10 km in extent, which are usually associated with the passage of a weather system. Finally, there are seemingly random movements of very small distances, less than 1 km, within the positioning accuracy range of the System Argos.

In a forced-balance calculation, one includes air stress and water stress, both functions of the velocity, and also the Coriolis force. Because of the large mass of the ice island, the Coriolis force is considerable and there is a counteracting pack ice stress, due to the pack ice accumulation on the right side of the moving island. The accelerations involved are usually small, but can be important.

Six islands are now instrumented with buoys supplying data through the ARGOS system. These deliver data on location, pressure, temperature and, on the largest one, wind speed, wind direction, peak wind and the instantaneous wind at a height of 2 m above the ice.

Coastal zones in 35 m water depth or more will be subjected to these ice islands on their first pass several years from now. The potential for interaction between one of these ice islands and a production structure could be quite significant. Some of these islands will go around the Beaufort gyre, and some will undoubtedly come back in 5 to 10 years, by which time they will have less freeboard, and so can be expected in shallower water (Sackinger 1986).

### KEMI I

The Finnish lighthouse KEMI I in the Gulf of Bothnia has been used for three successive winters to measure forces due to moving ice; first against a vertical cylinder and later, when a conical collar was added, against an instrumented cone. Agreement with finite element calculations for low loading rates below fracture has been satisfactory for the cylindrical case. Bending failures against the cone are being analyzed, and future experiments involving the controlled towing of artificially-thickened ice floes against the structure are also planned.

The KEMI I Lighthouse is a cylinder about 5.8 m in diameter, located in 10 m of water. It is made of concrete and has a caisson retaining base. In the first winter, the approach was to put an array of stress transducers and strain gauges in the ice sheet surrounding the lighthouse. During that winter the movements were very small; however, three stress events took place which caused a certain amount of creep and deformation of the ice next to the lighthouse, although not any fracturing. Stresses were measured in the surrounding ice sheet. Then the resulting stress on the lighthouse was calculated by the finite element technique. At the same time the lighthouse had been calibrated to measure total force. This is about the closest anyone has come to having a real structure which can be used to measure the total force of ice on it, although there is one in the Sea of Okhotsk in Japan that has been calibrated by a similar approach.

It was found that the forces are of the same order of magnitude whether they are calculated on the basis of the stress in the ice sheet, or whether they are measured by the total force approach. About two megatons were calculated in that particular experiment. The assumption was made that the ice sheet was of uniform thickness, which was not actually the case. Nevertheless, the agreement found is reasonable, considering that the ice thickness varied around the lighthouse (Kajaste-Rudnitski and Sackinger 1986).

In the second year's experiment, a conical collar was added, and the ice then broke in a flexural manner, riding up on the conical collar. Again, strain and stress gauges were in the ice sheet. There were several days of active movement and data were collected as the ice rode up the conical collar. The deflection of the total structure was available, pressure was measured between the collar and the lighthouse, and between the collar and the foundation. There were also a large number of strain gauges embedded inside the cone during its manufacture. Some of the results are presented by Niemenlehto and Nordlund (1986).

In a proposed future experiment, the cone will be left in place and an artificially-thickened piece of ice of a known, uniform thickness (2 to 3 m) will be created. This will be produced some distance away. After the annual ice floes have started to break up and move out, the thickened ice will be towed by an icebreaker to the vicinity of the lighthouse and pulled up against it. The velocity of impact will be known, as will the

area where the impact takes place. The shape and size of the floe will be known, as will the nature of the ice. It will be freshwater ice because the nearby water is of very low salinity. The idea is to keep the speed of the interaction fairly low so the lighthouse is not damaged, and study the fracturing of the floe as it rises up the cone, breaks, and comes to a stop. The study will be similar to the Hans Island experiment except that the floe will be prepared to specifications and the velocity will be controlled. Similar ice floe instrumentation as in the Hans Island experiment can be used to measure total forces at the same time.

### SPRAY SEA ICE

Near the edge of pack ice, spray sea ice is accreted on the superstructure of ships, service vessels, and offshore structures. Four different mechanisms for spray ice accretion are known, and examples of such ice obtained under field conditions have been examined. The bond between spray ice and several offshore structure coatings has been measured and a low bond strength, in the range 4-7 kPa, has been found for graphite paint, polyethylene, and acrylic paint.

Spray ice can develop in several different ways on a structure. The first is when fog droplets condense on a structure. These subsequently freeze, forming large crystals of low-salinity ice which are intimately bonded to the structure, resulting in high bond strength. A second case is water droplets which freeze upon impact. In this case, very small crystals of high-salinity ice are formed. The third case occurs when there is partial freezing in the air column. In this case, ice is of low salinity, being formed during the transit of the droplet through the air. This is followed by freezing upon impact, and the resulting very saline brine drains away. In the fourth case, frazil ice particles form in the water column itself. By wave action these are thrust into the air and carried by the wind to the surface of the structure where they freeze. These have developed a certain crystal orientation and may have dirt or marine debris included in the crystal structure.

All four kinds of ice have been observed in icing events. Measurements have been made of the bond strength between cylinders and these kinds of ice using a torsion apparatus. There is considerable variation in salinity and density, depending on which of the four processes is operating. The torsion technique has been used to measure the bond strength, which showed that the bond with metal (Type 316 stainless, for example) is around 28 kPa shear strength; for graphite paint, 5.2 kPa, acrylic paint 6.5 kPa, and 7.3 kPa, and for polyethylene 4.4 kPa, respectively. The Inerta 160 coating on icebreakers is intermediate between these extremes at 14 kPa. Teflon is surprisingly high at 24 kPa (Sackinger *et al.* 1986).

More data are needed before firm conclusions can be drawn, but it appears that there are two or three substances that will reduce the bond strength by a factor of 4 or 5. Graphite paint is the most promising on vertical surfaces because of its durability. Further research should be done and the results will depend on which of the four kinds of ice is considered as most important in the investigation.

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**APPENDIX A**  
**LIST OF ATTENDEES**

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July 22-23, 1986

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**APPENDIX B**  
**SELECTED BIBLIOGRAPHIES**

**NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION  
OUTER CONTINENTAL SHELF ENVIRONMENTAL ASSESSMENT PROGRAM  
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RELATED TO SEA ICE**

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