POAC 89

The 10th International Conference on Port and Ocean Engineering under Arctic Conditions.
June 12-16 1989, Luleå, Sweden

VOLUME 2

Edited by

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Department of Civil Engineering
Luleå University of Technology
Luleå, Sweden

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These proceedings comprise the papers to be presented at the 10th International Conference on Port and Ocean Engineering under Arctic Conditions in Luleå, 12-16 June 1989. About 140 papers have been submitted and accepted, all of a high scientific standard.

The POAC-conferences have been organized biennially since 1971, when Professor Per Bruun at the Norwegian Institute of Technology in Trondheim took the initiative of organizing a conference within the growing area of arctic technology.

This vast field embraces topics from Ice Morphology and Ice Mechanics over Ice/Structure Interaction, Ice Breaking Technology and Ice Navigation-Management to Offshore Platforms, Productions Systems and Operation Experiences in the Arctic as well as Climate and Ice Forecasting. Since 1971, arctic technology has developed tremendously and the POAC Conferences have contributed greatly to the scientific and industrial exchange of ideas. After Trondheim 1971, POAC has been held in Reykjavik, Iceland 1973, Fairbanks, Alaska 1975, St John’s, Newfoundland 1977, Trondheim 1979, Quebec, Canada 1981, Helsinki, Finland 1983, Narssarssuq, Greenland 1985 and Fairbanks, Alaska 1987.

Since the Conference is taking place in northern Sweden, the Gulf of Bothnia and the Baltic is, of course, dealt with to some extent. Here the Remote Sensing Project BEPERS and the new Swedish Ice Breaker Oden could be mentioned.

Most of the papers presented at POAC-89 are printed in Vol. 1 and 2 of the Proceedings available at the Conference. However, Keynote Lectures and some papers will appear in a post conference volume, Vol. 3, also containing discussions etc.

It is an honour for the town of Luleå and for Luleå University of Technology to host this 10th POAC. The town of Luleå was founded in 1621 as a commercial centre and harbour for the important trade with the inland of northern Sweden. Luleå is situated close to the Arctic Circle but its harbour has year-around-traffic even though the Gulf of Bothnia is ice-covered from December to May. Luleå University is young, it was opened
in 1971, and has, among other areas, focused on Cold Region Technology.

This conference was organized with financial support from the Ministry of Technology, Luleå University of Technology, the town of Luleå, the COLDTECH-program, the Swedish Building Research Council, the National Swedish Administration of Shipping and Navigation and Scandinavian Airlines. We are indebted to the POAC International Committee for their guidance. A special thank goes to the President of POAC, Mr Alf Engelbrektsson and to Prof. Per Bruun for their encouraging support.

The local planning of the conference has been carried out by a small Organizing Committee at Luleå University which, however, has been supported by an Advisory Committee with representatives from Universities, Research Centres, Industries and Authorities. The Advisory Committee is gratefully acknowledged. We are also indebted to the many reviewers for their successful work of improving the papers for the conference.

A special acknowledgement is given to Ms Christina Nilsson who has administrated all questions concerning papers, reviewers and all the work with these proceedings.

Finally, we wish to thank all the keynote lecturers and all the authors of papers for their important scientific contribution as well as all participants for their interest in the conference and their contribution.

Kennet B.E. Axelsson                   Lennart A. Fransson
1. SEA ICE PROPERTIES

1.1 Ice Morphology, Ice Dynamics, Ice Drift etc

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## 2. ICE/STRUCTURE INTERACTION

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ABSTRACT

Many offshore activities require the knowledge of the interaction of waves between two adjacent floating bodies. The two bodies affect the fluid loading on each other. The incident waves are diffracted and as a result of the motion of the bodies, waves are radiated outwards. In order to find an analytical solution, the problem is here considered from a theoretical viewpoint using a two-dimensional linearised theory of water waves. An eigenfunction expansion for the velocity potential is constructed for rectangular domains around the bodies and then matched on the common boundaries to determine the unknown coefficients in the expansions. The exciting forces, added mass and damping coefficients are given special attention.

1. INTRODUCTION

To better understand the collision courses and interaction between two bodies floating in the vicinity of each other, a research program has been developed at the Dept of Marine Structural Engineering, Chalmers University of Technology, Göteborg in collaboration with the offshore company GVA, Göteborg. The application was intended to be a small iceberg floating close to an offshore platform, a supply vessel close to an offshore platform, or any other case where two bodies are fixed or floating close to each other. In the research presented in this paper the main interest was to find a method to solve the hydrodynamic problem with two bodies floating adjacent to each other thus coupling their motion by fluid loading.

Finite element methods (FEM) and integral methods are two numerical methods which can be used. An analytical method to solve the problem is to match the eigenfunction expansions. The analytical method was chosen in order to see how
certain parameters affect the results. Another advantage that can not be ignored is that this method gives higher numerical accuracy and consumes much less computer time than purely numerical solutions.

McIver (1986) has solved a symmetrical two-dimensional problem with two floating, fixed bridges by matching eigenfunction expansions. Other authors, e.g. Sayer and Liang (1986) and Van Oortmerssen (1979) have imposed three-dimensional solutions for the two body problem, based on numerical solutions by using the integral method and the FEM-method respectively.

Here two rectangular cylinders, horizontally floating in a fluid at finite depth are studied. Hydrodynamic effects are assumed to be two-dimensional, so the results are relevant for long cylinders. Solutions can be made for both fixed and free-floating bodies. At present two bodies are considered but the method can easily be extended for any larger number of bodies.

2 GOVERNING EQUATIONS
2.1 Formulation of the problem

Consider two bodies floating on the surface of a fluid of uniform depth h, as illustrated in Figure 1. The bodies are shaped as parallel cylinders of rectangular cross-section and are of sufficient length so that for a normal wave incidence the problem could be considered as two-dimensional. Cartesian coordinates \( x = (x,z) \) are chosen with the z axis pointing upward and the x axis on the undisturbed free surface.

Three types of boundaries are of interest: 1) The air-water interface which will be called the free surface, 2) the wetted surfaces of the two bodies and 3) the fluid bottom. Let the equation of the free surface be \( z - \zeta(x,t) = 0 \), where \( \zeta \) is the height measured from \( z = 0 \). A plane wave of amplitude \( a_0 \) and
frequency \( \omega \) is assumed to be incident from the large negative \( x \)-direction:

\[
\zeta(x,t) = a_0 \cos(kx - \omega t) = \text{Re}\{a_0 e^{i(kx - \omega t)}\}
\]  

(1)

where \( i \) is the imaginary unit \((-1)^{1/2}\) and \( k \) is the wave number defined by the dispersion relations for the different regions. For the convenience of mathematical manipulation, the exponential form is here preferred. The wave amplitude is assumed small so that a linear theory is justified.

2.2 Water waves in constant depth

For an inviscid irrotational flow, the velocity \( \mathbf{u} = (u, w) \) can be expressed as the gradient of a scalar potential \( \Phi(x, z, t) \), i.e. \( \mathbf{u} = \nabla \Phi \). Conservation of mass requires that the potential satisfies Laplace equation

\[
\nabla^2 \Phi = 0
\]  

(2)

in the fluid domain. The velocity potential must also satisfy the boundary conditions and an appropriate radiation condition, which is the Sommerfeld radiation condition ensuring that waves radiated away to infinity do not return. The linearized theory for small amplitude waves requires the free surface boundary condition

\[
\frac{\partial \Phi}{\partial t} + g \frac{\partial \Phi}{\partial z} = 0 \text{ at } z = 0
\]  

(3)

where \( g \) is the acceleration due to gravity, and the boundary condition of an impenetrable body

\[
\frac{\partial \Phi}{\partial n} = V_n = \sum_{k=1}^{3} v_k n_k
\]  

(4)

where \( V_n \) is the velocity of the body surface in the normal direction \( n \) and \( v_k \) is the velocity of the body in each of the three degrees of freedom. The quantities \( n_1 = n_x \) and \( n_2 = n_z \) are direction cosines of the outward unit normal, while \( n_3 = x_G n_z - z_G n_x \) describes the rotation of the body. Hence, on the bottom one has

\[
\frac{\partial \Phi}{\partial z} = 0 \text{ at } z = -h
\]  

(5)

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The total pressure inside the fluid can be related to $\phi$ by linearizing the Bernoulli equation

$$p = -\rho gz - \rho \frac{\partial \phi}{\partial t}$$  \hspace{1cm} (6)

where $\rho$ is the density of the fluid. The first term, $\rho gz$, is the hydrostatic contribution, whereas the second term is the hydrodynamic contribution to the total pressure.

2.3 Method of solution

Assuming that the resulting motion of the plane wave in equation (1) is time harmonic with frequency $\omega$, the velocity potential may be written as $\phi(x, z, t) = \text{Re}\{\phi(x, z) e^{-i\omega t}\}$. For brevity the sign $\text{Re}\{\ldots\}$ is omitted in the following.

It is convenient to divide the problem into two parts:

1. The incident wave scattered by the two bodies kept in fixed positions.
2. The waves produced as the two bodies are forced to oscillate harmonically, $a_{jk} e^{-i\omega t}$, in otherwise still water. $j=1,2$ are the two bodies and $k=1,2,3$ are the three modes of motion.

The linearity of the problem allows these two motions to be superposed, with the wave force of the incident wave problem providing the forcing function for the forced-motion problem.

The potential for the scattering of the incident wave by the fixed bodies can be separated into the incident wave potential, superscript $i$, and the scattered wave potential, superscript $s$. The body boundary condition (4) is represented by the sum of three individual components for each of the two bodies. It is therefore useful to divide the potential, describing the waves due to the forced motion, into six components each. These may be separated into a "forced" potential and a "scattered" potential. Thus

$$\phi = a_0(\phi^i + \phi^s_{00}) + \sum_{j=1}^{2} \sum_{k=1}^{3} (-i\omega a_{jk})(\phi^f_{jk} + \phi^s_{jk})$$  \hspace{1cm} (7)

where $\phi^i_{jk}$ is the potential only due to motion in the $k$th direction of the $j$th body. Each of the potentials must satisfy the Laplace equation

$$\nabla^2 \phi^i = \nabla^2 \phi^s = \nabla^2 \phi^f = 0$$  \hspace{1cm} (8)

and the free surface boundary conditions
\( \frac{\partial \Phi}{\partial z} - \frac{\omega^2}{g} \Phi = \frac{\partial \Phi}{\partial z} - \frac{\omega^2}{g} \Phi = 0 \) \hspace{1cm} (9)

at \( z = 0 \). The body boundary conditions are

\[ \frac{\partial \Phi}{\partial n} = - \frac{\partial \Phi_0}{\partial n} \]

\[ \frac{\partial (\Phi^f + \Phi^s)}{\partial n} = n_k \quad j=1,2 \text{ and } k=1,2,3 \] \hspace{1cm} (10)

The solution of the velocity potentials proceeds by taking eigenfunction expansions valid in each of the five regions marked in Figure 1 and matching them on common boundaries.

3 THE VELOCITY POTENTIALS

The scattering potentials are solved by dividing the two-dimensional fluid domain into rectangular sub-domains, each bounded below by the horizontal bottom and bounded above by either a fixed boundary or the free surface. For each sub-domain the velocity potential may be expressed in terms of a complete set of eigenfunctions obtained from Laplace’s equation by separating the variables. Where the free surface forms the upper boundary the general eigenfunction expansion takes the form

\[ \Phi_{jk} = \left\{ A_{1jk} e^{ik\xi} + B_{1jk} e^{-ik\xi} \right\} \frac{\cosh k(z+h)}{\cosh kh} + \]

\[ + \sum_{n=2}^{\infty} \left\{ A_{njk} e^{-\alpha_n z} + B_{njk} e^{\alpha_n z} \right\} \frac{\cos \alpha_n(z+h)}{\cos \alpha_n h} \] \hspace{1cm} (11)

where \( \xi = x - l_1 \) in region \( Q_1 \), \( \xi = x - \frac{1}{2}(l_3+l_2) \) in region \( Q_3 \) and \( \xi = x - l_4 \) in region \( Q_5 \). The Sommerfeld condition require in region \( Q_1 \) that all \( A_{njk} = 0 \) and in region \( Q_5 \) that all \( B_{njk} = 0 \). The wave number \( k \) and \( \alpha_n \) are determined from

\[ \frac{\omega^2}{g} = k \tanh kh = -\alpha_n \tan \frac{\alpha_n}{h} \] \hspace{1cm} (12)

For the second type of fluid sub-domain bounded above by a fixed boundary, the general eigenfunction expansion is of the form
\[ \phi_{jk}^S = A_{1jk} \frac{\xi}{b} + B_{1jk} + \sum_{n=2}^{\infty} \left\{ A_{njk} e^{-\beta_n \xi} + B_{njk} e^{+\beta_n \xi} \right\} \cos \beta_n (z+h) \] (13)

where \( \xi = x - \frac{h}{2}(1_2 - 1_1) \) and \( b = \frac{h}{2}(1_2 - 1_1) \) in region \( \Omega_2 \), \( \xi = x - \frac{h}{2}(1_4 - 1_3) \) and \( b = \frac{h}{2}(1_4 - 1_3) \) in region \( \Omega_4 \), and

\[ \beta_n = \frac{(n-1)\pi}{h - d_1} \] (14)

The incident wave potential satisfies equations (8) and (9) and is specified in complex form as

\[ \phi^i = -i \frac{k}{\omega} e^{+ik(x-1_1)} \frac{\cosh k(z+h)}{\cosh kh} \] (15)

The forced motion potentials are, in heave motion, given by

\[ \phi_{j2}^f = \frac{1}{2(h-d)} \left\{ -(L-x)^2 + (h+z)^2 \right\} \] (16)

where \( L = \frac{h}{2}(1_1 + 1_2) \) for body 1 and \( L = \frac{h}{2}(1_3 + 1_4) \) for body 2. There is no motion of any upper (or lower) boundary in the surge motion, and hence there is no contribution to the total velocity potential from this kind of motion. The pitch motion contributes with the term

\[ \phi_{j3}^f = \frac{(x-L)}{6(h-d)} \left\{ -(L-x)^2 + 3(h+z)^2 \right\} \] (17)

where \( L \) is as above.

The unknown coefficients \( A_{njk} \) and \( B_{njk} \) are determined by satisfying the vertical boundary conditions between regions. The matching of two regions at the boundary is achieved by imposing continuity of pressure and horizontal velocity, which is equivalent to continuity of \( \phi \) and \( \partial \phi / \partial x \). This gives a system of equations which includes functions of \( z \). Multiplication of each equation by each of the orthogonal eigenfunctions and integration over their respective ranges of validity give a system of equations, from which the unknown coefficients can be determined.

The eigenfunctions and eigenvalues are defined by equations (11), (12) and (13). They individually satisfy the lower and upper boundary conditions, thus ensure that \( \phi \) itself satisfies these conditions. The method of matched eigenfunction expansions will, for large \( n \), satisfy the vertical boundary conditions.
The forces and moments on the two bodies are made up of components due to the hydrostatic and hydrodynamic pressure in equation (6). The equations of motion may be written in matrix form as

$$-\omega^2 [M_j] a_j = - [C_j] a_j + \rho \int_{S_j} \frac{\partial \Phi}{\partial t} \mathbf{n} \, dS = - [C_j] a_j + \mathbf{F}_j^e + \mathbf{F}_j^f \quad j=1,2 \quad (18)$$

where $a_j = (a_{j1}, a_{j2}, a_{j3})$, $\mathbf{n} = (n_1, n_2, n_3)$ and $S_j$ is the equilibrium surface of body $j$. The mass matrices $[M_j]$ and hydrostatic stiffness matrices $[C_j]$ are simply derived for the given body configuration. The hydrodynamic forces and moments are expressed as the exciting forces $\mathbf{F}_j^e$, due to the incident and scattered potentials, and the components $\mathbf{F}_j^f$ due to the forced potentials. The latter forces can be decomposed into components which are in-phase and out-of-phase with the acceleration:

$$\mathbf{F}_j^f = \omega^2 \rho \sum_{m=1}^{2} \sum_{k=1}^{3} a_{mk} \int_{S_j} (\Phi^{f}_{mk} + \Phi^{s}_{mk}) \mathbf{n} \, dS =$$

$$= \sum_{m=1}^{2} \{ (\omega^2 [\mu_{jm}] + i\omega[\lambda_{jm}]) a_m \} \quad j=1,2 \quad (19)$$

where $[\mu_{11}]$ and $[\mu_{22}]$ are the added mass matrices and $[\lambda_{11}]$ and $[\lambda_{22}]$ are the radiating damping coefficient matrices, while $[\mu_{12}] = [\mu_{21}]^T$ and $[\lambda_{12}] = [\lambda_{21}]^T$ are in-phase and out-of-phase hydrodynamic interaction coefficient matrices. The components of these matrices are given by

$$(\mu_{jm})_{ik} = \rho \int_{S_m} \text{Re}(\Phi^{f}_{jk} + \Phi^{s}_{jk}) n_i \, dS \quad (20)$$

$$(\lambda_{jm})_{ik} = \rho \omega \int_{S_m} \text{Im}(\Phi^{f}_{jk} + \Phi^{s}_{jk}) n_i \, dS$$

Equations (18) and (19) give the equations of motion in the form

$$\{-\omega^2 [M_j] + [\mu_{jj}]) - i\omega[\lambda_{jj}] + [C_j] a_j + \{-\omega^2 [\mu_{jm}] - i\omega[\lambda_{jm}]) a_m = \mathbf{F}_j^e \quad (21)$$
where \( m = 2, 1 \) when \( j = 1, 2 \) respectively.

5. RESULTS

The expansions series of the velocity potentials converge quite rapidly. A numerical value for added mass, damping or hydrodynamic forces on the bodies with a relative error less than 1\%, needs less than 10 terms in the series, while 20 terms usually gives a relative error of less than 0.1\%. However, the first term in the series already clearly indicates the fourth coming shape of the curves describing added mass, damping and hydrodynamic forces as a function of some parameter, e.g. the frequency of the incoming wave or the distance between the bodies.

Hence, two kinds of results can be obtained from the equations above. Numerical results may be found with high numerical accuracy, using a large number of terms in the series expansions of the velocity potentials. Analytical results may be found using only one or two terms of the series. The analytical results, with low numerical accuracy, can be used to study the influence of some specific parameter on the hydrodynamic quantities. Here only some results from the numerical solution are discussed.

A computer program which can handle one and two floating bodies (and which can be easily extended to handle any number of floating bodies) has been written. It first determines the coefficients \( A_{njk} \) and \( B_{njk} \) in the velocity potentials and then calculates the added mass, damping and interaction coefficient matrices. Thereafter, the equations of motion are solved.

![Graph](image)

Figure 2. Single body problem. Added mass (a) and damping coefficients (d) in heaving. For rectangular cross-section with breadth 0.40 m, draught; (1) 0.20 m, (2) 0.10 m, (3) 0.05 m. Water depth is equal to 2.0 m.
When comparing these results with those of other authors, a good agreement is found except at small values of the frequency of the incoming wave or for small values of the forced motion. This holds both for wave forces on two fixed bodies, (e.g. McIver (1986) who studied wave forces on adjacent floating bridges), and for added mass and damping for one and two floating bodies. Vugts (1968) studied the hydrodynamic coefficients of two-dimensional cylinders of various cross-sections. Added mass and damping in heaving for a rectangular cross-section with breadth 0.40 m and draught 0.20-0.10-0.05 m are shown in Figure 2 for a water depth equal to 2.0 m. These curves differ from Vugts' curves for low frequencies. Added mass does not go to infinity and damping does not go to zero when the frequency goes to zero. This is due to the fact that our curves are calculated with a theory for finite depth. No approximations have been made due to the depth.

\[ \frac{b \cdot d \cdot \rho}{b \cdot d \cdot \rho} \]

Figure 3. Two bodies 10 m apart, with rectangular cross-sections, breadth 12.0 m and draught 6.0 m. Upper curve is the added mass in z-direction for heave. The lower curve is the interaction coefficient. The dashed line is the added mass for a single body problem.

The Sayer and Liang (1986) three-dimensional integral equation method, for studying of wave interaction between barges, differs from our result for small and large frequencies. In Figures 3 and 4 added mass and damping are shown for two parallel bodies 10 m apart, equally sized and 50 m long, with rectangular cross-sections. The breadth is 12 m, the draught is 6 m and the water depth is 24 m. For small frequency values, added mass do not go to infinity neither does the damping coefficient go to zero, which is due to the finite depth used
in our equations. For frequency equal to 1.756, the resonance phenomenon due to a standing wave between the bodies is evident.

The dotted lines in Figures 3 and 4 are added mass and damping in the case of only one body. As expected, damping in the case of one, and of two, bodies has the same limiting values for small and large frequencies. Added mass in the case of one body is equal to the sum of the added mass and the interaction coefficient in the two body problem at small frequencies (since both bodies move with the same amplitude in a very long wave).

Figure 4. Damping in z-direction for heave. The lower curve is the interaction coefficient. The dashed line is the damping coefficient for a single body problem.

6. CONCLUSIONS

Although the results shown in this paper have concentrated on added mass and damping, some general conclusions can be drawn:

1. The eigenfunction expansion of the velocity potentials gives a very rapid and accurate method for calculating the hydrodynamic interaction of two (or more) bodies.

2. For finite depth the value of added mass does not go to infinity and the value of damping does not go to zero.

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MEASUREMENT OF IMPACT FORCES
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ABSTRACT

This paper reports the results of impact tests conducted on first year sea ice in Resolute Bay, North West Territories. The instrumentation was chosen to ensure the capture of signals at the instant of highest dynamic load. Tests were conducted at impact velocities from 1 m/s to 3.4 m/s. Independent measurements of global acceleration, local contact force, and depth of penetration were made. Peak accelerations up to 400 g's were observed, and local forces on a contact area of 0.712 cm² gave pressures as high as 60 MPa. The peak impact events had rise times of 200 μs to 880 μs. The acceleration and local contact force were determined as functions of time and depth.

1. INTRODUCTION

A review on iceberg impact by Nevel (1986) points out that little information is available on the transient response and failure behaviour of ice at impact.

Low velocity impact experiments in ice were carried out by Lange and Ahrens (1987). They report crater shape, dimensions, volume and morphology related to impact energies. El-Tahan et al. (1988) measured acceleration and total force on a cylindrical indenter impacting iceberg ice at 2 m/s. Impact pressure time histories show sharp initial peaks up to 21 MPa. The dynamic characteristics of an ice plate on impact are discussed in
Epifanov (1985) and (1986), and other papers by the same author. The drop ball tests reported earlier by Likhomanov and Kheisin, Khrapatyi and Tsuprik, and others were reviewed by Epifanov (1986) and the effects of instrumentation limitations on the apparent results were noted. Epifanov used a piezoelectric accelerometer to study global force as a function of depth for a spherical impactor. He showed that deformation processes and failure modes in the ice can be related to particular intervals in the acceleration time histories.

The purpose of the present study is to determine, with high resolution, the transient response of sea ice at impact, and in particular to characterize both the global and local contact forces as functions of depth of penetration. Preliminary tests were conducted in the cold room of the Institute for Marine Dynamics on freshwater S2 ice, Chin et al. (1988). The impact apparatus, transducers, and other instrumentation were assembled in Resolute for the sea ice tests.

2. EXPERIMENTAL METHODS

The test ice was obtained from a trench in the sea ice on Resolute Bay. A rectangular specimen 80 cm x 50 cm, with thickness between 5 cm and 28 cm, was prepared for each impact test.

The impactor and support frame are shown in Figure 1. The 1.17 m long drop hammer with the rigidly attached impactor head drops freely through a 20.32 cm diameter vertical bearing. The lock-release mechanism allows a range of drop heights to be selected. For the Resolute tests, the drop heights ranged from 5 cm to 65 cm, and the total mass was 54 kg. The impactor head is a 10.16 cm diameter segment of a sphere with radius 10.00 cm, screw mounted on a cylindrical steel chuck.

A piezoelectric force transducer, with natural frequency \( f_n = 75 \text{ kHz} \), (max. range 45 kN) was fitted inside the impactor head. A conical steel plug with a contact surface area of 0.712 cm\(^2\) transferred the impact load from the centre of the impactor face to the transducer. Two small piezoelectric accelerometers \( f_n = 125 \text{ kHz} \) were fitted into the top of the steel chuck. A third accelerometer was mounted on top of the drop hammer to monitor
the apparatus vibration. The displacement of the drop hammer was measured by a resistance potentiometer.

A schematic of the data recording and acquisition system is shown in Figure 2. The force, acceleration and displacement signals were recorded on a data recorder with a 10 kHz band width. A digital oscilloscope was used to digitize the analog signals at a sampling rate of 100 kHz, and to carry out further analysis.

The ice samples were rigidly mounted on the base of the rig using screw jacks, with the point of impact located precisely at the centre of the sample impact surface. After impact, the depth of penetration, the extent of spalling (horizontal and vertical dimensions) and the lengths of significant cracks were measured.

3. RESULTS AND DISCUSSION

The test results were screened to eliminate anomalous failure modes and impacts which showed compliance in the sample mounting. A typical retained data set, for a drop height of 25 cm, is shown in Figures 3 to 5. The specimen is 21.8 cm thick, with the long axis of the grains oriented perpendicular to the direction of impact. The damaged ice showed cracks radiating from the impact centre, spalling, and a layer of powdered ice just beneath the impactor. For the test series, ice temperatures ranged from -5 to -24°C.

The g-force shown in Figure 3 is the difference between the measured global acceleration and gravitational acceleration, multiplied by the mass of the impactor. The oscillations are pronounced in the first 1.8 ms after impact, and in most impacts there was a larger amplitude negative peak immediately following the first peak. The series of sharp peaks is followed by lower frequency, lower amplitude oscillations. The saw tooth pattern decays until the signal evens out after about 13 ms. The spectrum of this signal showed that these processes principally occurred at frequencies of less than 4 kHz, but there were modal contributions over a range of frequencies up to 12 kHz. The natural response frequency of the impactor is 16 to 18 kHz. Thus the oscillations suggest both stress waves in the impactor and damage effects in the ice specimen. Over the test series,
initial peaks as high as 211 kN, with rise times of about 180 µs, were recorded.

The average contact pressure, the ratio of the measured force to the area of the instrumented surface at the centre of the impactor face, is shown in Figure 4. From the instant of impact, the rise time is 640 µs to a peak pressure of 35.69 MPa. Over the range of drop heights in this test series, the peak pressure ranged from 14 to 60 MPa, increasing in proportion to the available potential energy, with rise times between 180 and 880 µs. The peak pressure occurs at the instant of maximum rebound of the g-force in Figure 3. The contact pressure declines during the sharp oscillation phase of the g-force, changes slowly during the reduced oscillations, then gradually declines as the g-force evens out.

The displacement-time curve for the same event is shown in Figure 5. High frequency oscillations due to the large range of the transducer were smoothed by a weighted running average. However, the change in curvature at impact was clear in the smoothed signal, and the final depth of penetration was close to that measured directly: 14.8 mm in Figure 5 compared with 15 mm in-situ measurement.

The momentum absorbed by the ice during penetration is equal to the integral of force over time, or the impulse. The impulse of the g-force and the local contact force, calculated from the data in Figures 3 and 4, is plotted against the depth of penetration in Figures 6 and 7 respectively. After the initial oscillations, the rate of change of g-impulse with depth is similar to the rate of change of local impulse with depth. These curves represent the global and local momenta respectively dissipated in ice damage.

The instantaneous local contact pressure $P_c$ as a function of penetration depth $y$ is shown in Figure 8 for the range of drop heights indicated by different line types. Clearly for higher initial impact velocities, larger stresses are required to reach a given penetration depth. As $P_c$ rises to its peak value, it has the form: $P_c(y) = A \cdot y$, where $A$ is the initial slope of the curve in Figure 8.

For an elastic half space, the contact force $F_c$ on beneath a
A spherical impactor of radius $r$ is

$$ F_c = 2 \cdot y \cdot E \cdot r / 3 \cdot (1 - \mu^2) $$

where $E$ is the Young's modulus and $\mu$ is the Poisson ratio. In the case of indentation, the ratio of effective stress to strain may be called, by analogy, the penetration modulus, $E_p$. Since the total force on the impactor is equal to or greater than the force on the instrumented surface, a minimum value for the penetration modulus, $E_p$, may be calculated from the observed values for $A$. For the typical case represented by the figures, $E_p \geq 57.8$ MPa. This is greater than the value $E_p = 14.4$ MPa given by Epifanov (1985), and much less than the value of the elastic modulus $E = 9.5$ GPa selected by Sinha (1979). The linear $P_c(y)$ relation is valid only up to the first peak of the local pressure, or, referring to Figures 3 and 4, until the instant of maximum rebound of the g-force. For the present tests, this time interval is 880 $\mu$s or less. It should be noted that at the unloading end of the $P_c(y)$ curves, there is a small decrease in penetration with decreasing pressure which is not shown in Figure 8.

4. CONCLUSIONS

(i) The test apparatus, instrumentation and data acquisition system proved to be adequate for dynamic tests on ice in the arctic environment. Independent records of global acceleration, local contact force, and depth of penetration at impact were obtained.

(ii) The relation between effective stress and strain in ice at impact is linear up to the first peak of the local contact pressure. In the present tests, this time interval is 880 $\mu$s or less.

(iii) The peak contact pressure, the depth of penetration at which the peak pressure occurs, and the energy or force required to reach a certain depth of penetration all increase with increasing impact velocity.
ACKNOWLEDGMENTS

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REFERENCES


Fig. 1 Overall view of impact test rig

Fig. 2 Data acquisition system for ice impact tests
Fig. 3 G_FORCE v TIME ... 25cm(1) [39]

Fig. 4 PRESS v TIME ... 25cm(1) [39]
Fig. 5 DISP v TIME ... 25cm(1) [39]

Fig. 6 G_IMPULSE v DISP ... 25cm(1) [39]
Fig. 7  L_IMPULSE  v  DISP ... 25cm(1)  [39]

Fig. 8  PRESS  v  DISP (DROP HEIGHT)
PENETRATION OF SPHERES AND RODS INTO ICE

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ABSTRACT

Small steel spheres, embedded in ice to a depth of one-half their diameter, were subjected to a range of loads. In a second series of tests, rigid steel rods extending through blocks of ice, were made to translate through the ice, by applying a range of loads through the protruding ends of the rods.

Both the spheres and the rods attained a constant rate of penetration under a constant load, after a very short time interval. The rates of penetration increased exponentially with an increase in the penetration stress.

1. INTRODUCTION

Interaction between rigid bodies and ice occurs in instances such as: anchors embedded in ice, laterally loaded piles in ice or ice-rich soils, and structures resting on ice sheets. As well, much of the creep behaviour of frozen soils, particularly ice-rich soils, can be attributed to the interaction between the "rigid" soil particles and the ice in the voids. Consequently the nature of the interaction between a rigid body subjected to a force, and the ice in contact with it, is of interest in cold regions engineering.

Research into the behaviour of ice and frozen soils is being carried out at the University of Manitoba. The interaction between rigid steel spheres and ice was part of a study of the creep behaviour of frozen soil, whereas the interaction
between rigid steel rods and ice was part of a study of laterally loaded piles in ice. This paper combines the two studies. The test apparatus, procedure and results for each study are presented separately, and the results are then compared as to their similarities and differences.

2.0 PENETRATION OF SPHERES INTO ICE

2.1 Test apparatus and procedure

Four samples of polycrystalline ice were prepared in plexiglass molds, 108 mm in diameter and 120 mm in height. A mold was half-filled with supercooled water, (approximately -1°C), then ice chips were added to bring the water level to the top of the mold. The top and side of the mold were insulated and the mold was placed in a freezing cabinet, (-20°C), thereby freezing the samples unidirectionally upwards.

A steel ball, 11.57 mm in diameter, was placed at the centre of the top surface of each ice sample during the latter stages of freezing. The ball was held in place by a styrofoam cover with a hemispherical hole in its centre. A schematic of the ice sample and ball, drawn to scale, is included in Fig. 1.

When frozen, the samples were taken out of the freezing chest, placed in a cold room, (-3°C), and allowed to come into temperature equilibrium. The steel balls were then loaded by deadweight hangers and the assemblies were placed inside an insulated cabinet to avoid temperature fluctuations during the defrosting cycle of the cold room.

Initially loads of 62.8 N, 85.1 N, 107.4 N and 129.6 N were applied to the steel balls. The penetration of the balls, with time, was measured with mechanical dial gauges. After 1100 hours the loads were removed, rebound was permitted, and new loads of 151.8 N, 174.1 N, 196.4 N, and 216.8 N were applied. The tests were carried on for an additional 1100 hours.

2.2 Test results

Plots of sphere penetration versus time, after Domaschuk et al., 1986, are shown in Fig. 1. For first loading there was no significant initial instantaneous penetration.
of the spheres into the ice for all loads, except the 129.6 N load. There was virtually

Fig. 1 Penetration of spheres vs time (after Domaschuk et al., 1986)

no rebound associated with unloading, and no significant instantaneous penetration associated with reloading. Therefore the instantaneous penetration obtained for the 129.6 N load was considered to be an aberration, caused perhaps, by imperfect contact between the sphere and the ice.

The results indicate that the interaction between a rigid sphere and ice is predominantly one of steady state penetration for the range of stresses investigated. The penetration rates, as indicted by the slopes of the penetration-time data, are
seen to increase with an increase in load.

3. PENETRATION OF RIGID RODS INTO ICE

3.1 Test apparatus and procedure

The ice was prepared in steel cylindrical tanks, having a wall thickness of 12.7 mm, a diameter of 890 mm and a height of 610 mm. A steel rod, 76 mm in diameter, was centered axially in the tank, with the ends of the rod protruding beyond the top and bottom of the tank. A hole, approximately 126 mm in diameter, was provided in the centre of both the top and the bottom of the tank to accommodate the protruding ends and to permit the rod to be displaced laterally. A reaction frame was mounted on the side of the tank, and hydraulic cylinders were used to apply equal lateral loads to the two protruding ends of the bar. A freezing plate was clamped to the bottom of the tank. A schematic of the test apparatus is shown in Fig. 2.

The instrumentation consisted of thermocouples to measure ice temperatures, LVDT’s to measure lateral displacement of the bar, and load cells to measure the applied lateral loads.

The ice sample was formed in a cold room, (-2°C), by placing layers of seed ice crystals in the tank and flooding the layers from below, with tap water precooled to 0°C, a technique described by Kjartanson et al., 1986. The ice was isotropic and uniform with a density of 900 kg/m$^3$.

A lateral load was applied to the protruding ends of the rod by means of the hydraulic jacks. The load was held constant by regulating the gas pressure which activated the jacks. The test was continued until a lateral displacement of about 15 mm was reached. Time-displacement data were recorded frequently using a data acquisition system.

Four tests were carried out, at lateral loads of 34.8, 40.6, 46.5 and 52.3 kN.

3.2 Test results

Plots of rod penetration versus time are shown in Fig. 3. In all tests there was
an initial instantaneous penetration of approximately 2 mm, followed by penetration at a constant rate. The rates of penetration increased from 0.018 mm/hr for the smallest load, (34.8 kN), to 0.098 mm/hr for the largest load, (52.3 kN).

3.3 Comparison of sphere and rod penetration results

The problem of the sphere and rod penetration into ice should be analyzed as rigid indenters in contact with a viscoelastic medium. The two cases differ in that the sphere was only embedded half-way into the surface of the ice, whereas the sides of the rod were completely embedded within the ice. Thus the flow patterns of the ice around the sphere and the rod would be different. Solutions have been developed for a rigid spherical indenter in contact with a half-space, e.g. Hunter, 1960; Ting, 1966, but, to the writers' knowledge, a solution for a cylinder
embedded in a viscoelastic medium, has not been developed as yet. Such solutions require viscoelastic parameters to describe the ice, and these have not yet been determined for the ice in question. Consequently a very simple approach was used to see if there were any similarities between the penetration results of the spheres and the rods.

Fig. 3 Penetration of steel rods vs time

The loads applied to the spheres and rods were converted to an average resultant stress acting in the direction of penetration. The stresses, hereafter referred to as "penetration stresses", were computed by dividing the force, by the bearing area, which was taken to be one-half of the surface area. Plots of penetration rate versus penetration stress are shown in Fig. 4 for the spheres and rods. The penetration rate for both is seen to have increased exponentially with the penetration stress. The relationships may be expressed as:
The exponent, which reflects the rate of change in penetration rate with penetration stress, was considerably larger for the rods. Two factors that contributed to this are: the warmer temperature used in the rod study, (-2°C vs. -3°C), and the fact that the ice displacement was 3-dimensional in the case of the spheres and only 2-dimensional in the case of the rods.

3.4 Resistance to penetration

Coefficients of resistance of ice to penetration, defined as the ratio of penetration stress to the penetration rate, were calculated, and these are shown plotted as a function of penetration stress in Fig. 5. The coefficients decreased exponentially with an increase in penetration stress which is consistent with the physical concept that the resistance to penetration should approach zero as the stress approaches infinity.

Fig. 4 Penetration rate vs penetration stress
\[ \dot{u} = \dot{u}_0 \left( \sigma / \sigma_0 \right)^n \]  

(1)

in which:

- \( \dot{u} \) = the penetration rate, (mm/hr)
- \( \sigma \) = the penetration stress, (kPa)
- \( \dot{u}_0 \) and \( \sigma_0 \) are the coordinates of any arbitrarily selected point on the curve
- \( n \) = the exponent, which is temperature dependent

![Graph](image)

**Fig. 5** Penetration resistance vs penetration stress

The respective expressions for the spheres and rods are:

- **Spheres** \( (T = -3^\circ C) \)
  \[ \dot{u} = \dot{u}_0 \left( \sigma / \sigma_0 \right)^{2.4} \]  
  (2)

- **Rods** \( (T = -2^\circ C) \)
  \[ \dot{u} = \dot{u}_0 \left( \sigma / \sigma_0 \right)^{4.1} \]  
  (3)
The relationships linearized on a semi-log plot as shown in Fig. 6, giving rise to the following expressions:

\[
\text{Spheres (T = -3°C)} \quad \eta = 3.0 \times 10^9 \varepsilon^{-0.001} \\
\text{Rods (T = -2°C)} \quad \eta = 6.5 \times 10^8 \varepsilon^{-0.001} 
\]

It is interesting to note that the exponent was essentially the same for the spheres and the rods. The exponent reflects the rate at which the coefficient of resistance changes with the penetration stress. Since this is an intrinsic property of the ice, it is a constant, independent of the shape of the rigid body.

4.0 OBSERVATIONS

1. Rigid spheres and rods embedded in polycrystalline ice underwent predominantly constant rates of penetration under constant loads.
2. The rates of penetration increased exponentially with an increase in the penetration stress.

3. The coefficient of penetration resistance of the ice decreased exponentially with an increase in the penetration stress.

4. The constant rates of penetration of the rigid bodies under constant stress, may explain the tendency for ice-rich soils to exhibit quasi steady-state creep under constant stress.

5.0 REFERENCES


IMPACT CRUSHING STRENGTH OF ICE

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ABSTRACT
Testing techniques and experimental data acquired by many authors are examined. The impact crushing strength of ice can be defined via the specific impact crushing energy which is the impact crushing energy related to the volume of the crushed ice. This definition is used in conjunction with a mathematical model of ice/rigid body impact to describe ice impacts against ships and offshore structures. Relationships between the impact crushing strength and various impact characteristics introduced by other authors are established. The available experimental data gives approximate estimates for the magnitudes and variation range of the impact crushing strength for various types of ice and conditions, as well as for the effects of ice temperature, impact velocity and indenter's mass and shape. More studies are necessary to substantiate and quantify these preliminary conclusions.

INTRODUCTION

Any model developed for estimating ice-induced loads on a marine structure has to include certain mechanical properties of ice. A strength characteristic of ice is a necessary element of the models based on the limiting ice strength approach, implying that the ice-induced loads cannot exceed the force (or pressure) breaking this ice under corresponding loading conditions and ice failure modes. Similar to other engineering materials, ice has been tested in laboratory and field conditions to measure its strength under appropriate loading. Common methods of testing the ice strength at relatively slow loading or strain rates and the experimental data acquired to date satisfy, to a certain degree, the needs for designing fixed structures acted upon by slowly advancing ice fields. However, for structures subjected to ice impacts (ships and sometimes offshore structures) the quasi-static strength characteristics can be inappropriate for estimating impact loads. Moreover, the very concept of limiting the loads by the strength of ice as a solid material can become questionable in impact conditions. When
the removal of the fragmented ice from the contact zone is physically restricted, the
impact interaction does not finish when the contacting ice fails, but continues with the
crushing of the fragmented ice, propagating the crushed ice zone and extruding the
crushed ice mass. Which of the mechanical properties of ice govern the ice loads, how
they can be measured and interpreted in the design practice are the questions addressed
in this work.

EXPERIMENTAL DATA BASE

Three types of tests have been used in studying the impact crushing strength of
ice: drop-weight tests, pendulum impacts and deep penetrating ballistic impacts. The
first publication on drop-ball tests should probably be credited to Pounder & Little
(1959). They measured the crater diameter and calculated the "impact hardness,"
implying an analogy to the Brinell hardness:

$$H = \frac{Mh}{(RZ^2 - Z^3/3)}.$$  

Note, this is actually a ratio of the potential energy to the weight of the ice within the
 crater volume. For a multi-year ice tested in mid-summer conditions in Eastern
Canadian Arctic (Fox Channel), the values from $H = 660$ to 900psi ($4.5 - 6.2 \text{ MPa}$)
were reported. Drop-cone tests (cone apex angle = 40°, $M = 5\text{kg}$, $h = 1\text{m}$) were carried
out by Dementyev (1961) with the penetration depths measured. A "dynamic hardness"
of ice was then calculated as a ratio of the force ($F = Mgh/Z$) to the contact surface
area ($a = 1.21Z^2$). Values ranging from 5 to 30 kg/cm² (0.5 to 3 MPa) were reported
for Arctic ice (Kara and Laptev Seas). Perforation tests of laboratory made sea and
fresh-water ice slabs were reported by Ross (1969). Laboratory tests of dropping small
(1/2" to 1" in diameter) balls made of steel and plastic materials (teflon, nylon, acrylic)
on ice had been performed in CRREL (Yen et al, 1970) to study the rebound and the
coefficients of restitution (CR). The latter, defined as a ratio of the impact-to­
rebound velocities, characterizes to what degree the impact is elastic. The plastic
materials caused little or no damage to the ice and CR was found ranging from 0.9
(almost elastic impact) to approximately 0.5-0.3. The steel spheres always destroyed
the ice and CR varied from 0.3-0.4 (for smaller spheres at lower velocities) to 0.1. In
semi-log scale, CR linearly decreased with an increase in velocity and mass and with a
decrease in temperature (Fig. 1a). A multi-year program of drop-ball tests had been
carried out in late 1960's on the fresh-water winter ice cover of Lake Ladoga by
were dropped on the ice cover from heights ranging from 5cm to 1m. Accelerations of
the sphere and ice cover oscillations were recorded during and after the impact to
specify impact variables, such as indentation depth and velocity history (by integrating
the acceleration records), impact duration, coefficient of restitution, contact pressure
history averaged over the contact plane area. The specific crushing energy was defined
as a ratio of the irrecoverable impact energy to the mass of the ice displaced from the crater volume:

\[ e = \frac{E_I}{W} \]  

(2)

It was found that the specific crushing energy is almost insensitive to the impact velocity (Fig. 2) while the coefficient of restitution depends on the velocity decreasing with an increase in the velocity (Fig. 1b). The mean values of the specific crushing energy were found ranging from \(3 \times 10^7\) to \(14 \times 10^7\) erg/g. Since the ice density was \(0.9\) g/cm\(^3\) on the average, these values are equivalent to 3.3 and 15.4 MPa, correspondingly. The CR measured by Yen et al (1970) and Likhomanov & Kheisin (1971) are re-plotted together in Fig. 1c to specify the mass and velocity effects. The plot clearly shows that irrecoverable inelastic processes are always dominant during impacts of steel bodies against ice. For the ship/ice and structure/ice impacts when the impact speed range is the same as in Fig. 1a, b, c, but the impact mass can range from several tons to millions of tons, the elastic energy share does not exceed a few per cent at most. This fact substantiates the assumption of neglecting the elastic deformation of ice when analyzing impact ice loads on ships and structures.

The Kheisin's testing technique was reproduced by Khrapaty and Tsuprick (1976) who tested sea ice at various ice temperatures. No specific information on the tested sea ice was given by the authors. A cylindrical indenter with a semi-spherical end (R = 5mm) was used by Tsurikov & Veselova (1973) for drop-weight tests (M = 5kg, h = 1m) measuring the maximum penetration depth and calculating "dynamic hardness" H of ice as a ratio of the force \(F = Mgh/Z\), as defined by Dementyev) to semi-sphere's area \(2\pi R^2\). They observed H ranging from 10.5 to 34 kg/cm\(^2\) (1-3.4 MPa) for Antarctic ice and from 3.4 to 37 kg/cm\(^2\) (0.34-3.7 MPa) for North Caspian Sea ice.

Pendulum impact tests have been reported by Glen & Comfort (1983). A flat pendulum \((M = 1160\) and 640 kg; \(V \leq 5.6\) m/s) was used to crush an apex of a prismatic ice specimen of laboratory saline ice \((S = 6\) and 1 ppt; \(t_i = -2, -10, -25^\circ C\)) with the impact ice pressure history recorded from several pressure transducers installed on the pendulum hammer and with the force, mean pressure and contact area history computed from the transducers' records. The specific crushing energy defined as an energy-to-volume ratio was also computed for different ice temperatures and salinities. When Glen & Comfort's data are recalculated and \(e\) is plotted versus the kinetic energy, the plot (Fig. 3) does not reveal a definite dependence but, similar to Kheisin's data, implies a low sensitivity to the velocity.

A tip shaped as a semi-cylinder situated horizontally \((R = 25\)mm and \(L = 50\)mm) was used for the drop-weight tests by El-Tahan et al (1984). Samples of iceberg ice and laboratory made snow ice were tested \((M = 59.85\)kg, \(V = 2\)m/s) with acceleration, penetration depth and pressure histories recorded. The maximum values of the pressure, force, impact period and indentation depth are reported for the ice
A vertical cylinder (D = 150mm) mounted on a bifilar pendulum (M = 375kg) was used by Sodhi & Morris (1986) for impacting the vertical face of a floating sheet of laboratory urea ice 40 to 120mm thick at velocities ranging from 0.3 to 1.5 m/s. The data acquisition system recorded the velocity, acceleration, total force and local pressure histories for each ram. Based on the presented data and identifying the impact energy with the crushing energy, the Sodhi & Morris data can be used to plot the specific crushing energy versus impact velocity (Fig. 5) - no clear tendency is seen. For each of the tests the authors also report the bending strength of the ice. This is the only source to relate an impact characteristic and a strength of ice.

Dynamic crushing of ice has also been recently studied in continuous fast penetration tests using both flat (Timco & Jordaan 1988) and spherical (Johnson & Benoit 1987, Jordaan et al 1988 a, b) indentors. When compared with the inertial impact tests, the fast penetration tests have clearly demonstrated both similarity and difference in ice failure mechanisms. In both tests the ice fails in a cracking/crushing mode producing a pulverized mass being forcibly squeezed out from the contact zone.
Fig. 1 Coefficient of restitution: a—after Yen et al, 1970; b—after Likhanov & Kheisin, 1971; c—from both data sources

Fig. 2 Specific crushing energy; after Kheisin et al, 1973

Fig. 3 Specific crushing energy, based on data by Glen & Comfort

Fig. 4 Specific crushing energy, based on data by Garcia et al

Fig. 5 Specific crushing energy vs velocity and bending strength for urea ice, based on data by Sodhi & Morris

Fig. 6 Impact schematic and notations
At the same token, at certain conditions the fast penetration tests are characterized by significant cyclicity of the interaction process (and consequently, of the pulverized mass extrusion and the resulting forces) while the impact generates virtually a single pulse without noticeable cycles of higher frequency superposed. It should be noted however, that the stress rates in the fast penetration tests have been somewhat intermediate between the rates of static and impact interactions.

ANALYTICAL MODEL

The above mentioned data cannot be used in design practice unless some impact characteristics of ice are incorporated into an analytical model of ice/structure impact interaction. The format of using the experimental data is to be consistent with the model. Such a model has been developed by Kheisin et al (1975) using the drop-ball tests for studying the physics and mechanics of the impact and for obtaining a mathematical solution. The model was applied for deriving expressions for ice impact loads on a ship side hitting an ice floe (Kurdyumov & Kheisin 1974) and has been later generalized (Kurdyumov & Kheisin 1984, Tunik 1984) to include various applications ranging from drop-weight tests with various indenter geometries to ramming icebreaking and offshore structure/iceberg impacts (Tunik 1985, 1987). The model is based on idealizing the crushed ice as a visco-plastic medium being dynamically pressed out from the contact zone between a moving rigid indenter and the intact solid ice whose boundary retards under the indenter. The extrusion of the pulverized crushed ice mass has been documented in many experimental studies (Kheisin et al 1970, 1971, 1975; Khrapaty & Tsuprick 1986, Glen & Comfort 1983, Johnson & Benoit 1987, Jordaan et al 1988a, b). The crushed ice mass extrusion is described by a simplified Reynolds system of equations, which yields a differential equation connecting pressure $P$ and viscous layer's thickness $h$ (see Fig. 6):

$$
\frac{d^2P}{dr^2}h^3 + 3\frac{dP}{dr}\frac{dh}{dr}h^2 = -1.5 mV
$$

(3)

This equation contains no parameters characterizing any mechanical properties of solid uncrushed ice and only a single parameter "m" - viscosity of the crushed ice mass. When solving equation (3), it was assumed that the pressure distribution over the thickness of the viscous layer is linear:

$$
P = kh
$$

(4)

This assumption introduces another parameter characterizing the crushed ice mass, $k$, which has a dimension of force/length$^3$ (e.g. N/m$^3$ in SI units). Solving equation (3) with assumption (4) yields the basic relationship connecting three principal variables (instantaneous pressure $P$ on indenter's surface at a point with cylindrical coordinate $r$ and instantaneous velocity $V$ of the indenter) and two constants ($m$ and $k$):

$$
P = [(3mk^3) V (r_o^2 - r^2)]^{1/4}
$$

(5)

Final expressions for the ice impact load parameters such as the maximum impact force, pressure, depth of penetration and their histories, as well as the impact
duration, can be obtained by solving the ordinary equation of inertial motion of the indenter of mass \(M\) acted upon by resisting pressure \(P\) distributed over surface "a"  

\[ M(d^2z/dt^2) + \int_a P \, da = 0 \]  

(6)

All the expressions obtained by Kheisin et al. (1975) for a steel sphere dropped on a flat ice surface contain a single combination of the two constants of crushed ice \((3mk^3)\) powered to various exponents:

\[ F_{\text{max}} = K_F (MD)^{5/9} V^{11/9} (3mk^3)^{1/9} \]  

(7a)

\[ P_{\text{max}} = K_P (MD)^{1/9} V^{4/9} (3mk^3)^{2/9} \]  

(7b)

\[ Z_{\text{max}} = K_Z (M^{4/9} D^{-5/9}) V^{7/9} (3mk^3)^{-1/9} \]  

(7c)

For practical applications of these expressions in estimating the ice loads on ship structures, the authors introduced a single parameter called the "parameter of dynamic strength of ice" and denoted

\[ a_p = (6mk^3)^{5/24} \]  

(8)

which has an inconvenient and unusual dimension:

\[ [a_p] \sim \{[N \text{ sec/m}^2][N/m^3]\}^{5/24} \sim [N^{5/6} \text{ sec}^{5/24}/m^{55/24}] \]  

(9)

Its values could not be measured directly and had been approximately estimated by recalculating back from measured ice-induced stresses in ship structures. In further applications of Kurdyumov-Kheisin's model to various cases ranging from impact tests to ramming icebreaking (Tunik 1984, 1985, 1987), the product of \((3mk^3)\) has been used in another form:

\[ A = (3mk^3)^{1/4} \]  

(10)

which follows directly from (5) and also has an unusual dimension of MPa(\text{sec/m}^3)^{1/4}.

Typical values of \(A\), scaled from Kurdyumov-Kheisin's values of \(a_p\), range approximately from 2 to 10, while the relationship between \(A\) and \(a_p\) is obvious:

\[ A \sim a_p^{6/5} \]  

(11)

When "\(A\)" is used instead of "\(a_p\)", equations (7) are transformed as follows:

\[ F_{\text{max}} = K_F (MD)^{5/9} V^{11/9} A^{4/9} \]  

(12a)

\[ P_{\text{max}} = K_P (MD)^{1/9} V^{4/9} A^{8/9}, \text{ etc.} \]  

(12b)

Thus, the parameters \(a_p\) or \(A\) expressed by (8) or (10) represent the mechanical properties of ice in the model. They can be calculated from impact tests using equations (7) for spherical indenters, or as given in Appendix for other shapes. However, the physical meaning of either parameter is obscure, while its dimensionality and use are inconvenient. Moreover, almost all of the above mentioned experimental data sources do not contain some details which are essential for calculating the values of \(a_p\) or \(A\). These disadvantages can be eliminated by replacing the \((mk^3)\) derivatives with the specific impact crushing energy defined above and denoted "\(e\)". To find a relationship between \(e\) and \(A\) (or \(a_p\)), the energy and the volume should be defined.
The kinetic energy of a dropping steel ball is absorbed by several processes, namely elastic deformation of the ice, crack nucleation and propagation within the affected ice zone, crushing of solid and fractured ice in the vicinity of the impacting rigid indenter, partial removal (often far way) of the spalled and crushed ice out from the impact zone, compacting of the remaining crushed ice mass at the crater's bottom, stress waves generated within the tested ice (bending waves when an ice cover is tested) and perhaps, others. There is insufficient data to quantify all of these energy components, but they can roughly be distinguished in two groups: (a) irreversible energy associated with all types of ice failure, which will be called "crushing" energy, and (b) recoverable energy of elastic deformation and wave propagation, which will be referred to as "non-crushing" energy. Thus, \( E_c \) can be expressed as follows:

\[
E_c = \alpha \frac{0.5 M V^2}{\pi} = \alpha mg h
\]

where \( \alpha \) is the ratio of the crushing energy to the kinetic energy, i.e. \( \alpha = 1 - CR^2 \). As a first approximation one can assume \( CR=0 \) and \( \alpha =1 \). The volume of crushed ice is not easy to measure. A practical way consists in measuring directly the crater volume assuming that all crushed and broken ice is removed (as done by the Garcia et al), which is not necessarily true, especially for the pendulum and ballistic tests.

All other authors have not measured the volume but calculated it from measured imprint dimensions. Kheisin et al did this by identifying the crushed ice volume with the volume of the penetrated part of the sphere. Khrapaty & Tsumpick also used this definition but applied a factor of 2.6-2.8 to account for the cracked volume (nevertheless, they obtained the same values of \( \varepsilon \) as Kheisin et al). A factor of 2.4 was also used by Glen & Comfort. No justification was given for these factors. The above outlined experimental data sources contain mostly the penetration depth, at best. To estimate the crushed ice volumes from the penetration depth data for the drop-ball test, we have:

\[
W = \frac{\pi}{6} Z (3r_0^2 + Z^2) = \frac{\pi}{3} Z^2 (3R - Z)
\]

For shallow penetration depths: \( Z^2/3r_0^2 \ll 1 \) and \( Z/3R \ll 1 \) (which is a typical condition for drop-ball tests), thus

\[
\varepsilon = \frac{\alpha M V^2}{\pi D Z}
\]

Manipulating with (7), (12), (8) and (10), one can obtain for the drop-ball test:

\[
P_{\text{max}} = 1.20 \varepsilon
\]

\[
P_{\text{av,max}} = 0.90 \varepsilon
\]

\[
F_{\text{max}} = 1.60 (M D_0)^{1/2} \nu
\]

\[
Z_{\text{max}} = 0.564 (M/D_0)^{1/2} \nu
\]

\[
T = 1.515 (M/D_0)^{1/2}
\]

\[
A = 1.65 \varepsilon^{9/8} / (MD)^{1/8} \nu^{1/2}
\]

Equations similar to (16) can be obtained for other shapes of the indenter—see Appendix 1. It is also easy to estimate \( \varepsilon \) from the "dynamic hardness." The Pounder & Little's "impact hardness" is actually identical to \( \varepsilon \), while the Dementyev's dynamic
hardness is \( H = 0.114a_e \) (in consistent units). A brief summary of the magnitudes of \( e \) for natural and laboratory ice, recalculated from the discussed data sources using equation (15), is given in Table 1.

Thus, the specific impact crushing energy \( "e" \) represents the mechanical resistance of ice to impact penetration, has the dimension of strength and, thus, can be identified with the impact crushing strength of ice - the name used in the title. Priority of this conclusion should be credited to Nevel (1986) who initially defined the impact crushing strength as a force-to-projected area ratio and then, using the Kurdyumov–Keisin's model, expressed the impact pressure analogously to equation (16a).

**CONCLUSIONS**

1. Impact of rigid bodies against ice, accompanied by extensive destruction of the ice, is predominantly inelastic. This fact is characterized by low values of the coefficient of restitution as compared with unity. The coefficient decreases with an increase in velocity and mass of the impacting body. For the range of velocities and masses typical for ice/ship (structure) impact, the restitution coefficient can virtually be taken equal to zero. For drop-ball tests the rebound may be noticeable at slow velocities (\(< -1\) m/s) and small masses (\(< -10\) kg).

2. The impact crushing strength appears to be an appropriate parameter to characterize the resistance of ice to impacts against engineering structures. Using this parameter in conjunction with the ice/structure impact model enables one to describe properly the physical nature of the impact and to predict the impact ice loads on ships and offshore structures. The resulting expressions for ice loads on various structures can be presented in a form similar to (16)–see also Appendix.

3. The impact crushing strength defined as the ice crushing energy per a unit of the crushed ice volume has a simple and convenient dimension of \( J/m^3 \) which turns to be identical with the strength unit (Pa). The available experimental data for natural fresh-water and sea ice for a wide range of environmental conditions (from decaying summer saline ice to cold fresh-water laboratory ice) vary approximately from 0.4 to 30MPa, i.e. within two orders of magnitudes. The published data often contains insufficient information on the tested ice, testing conditions and measurements. As a result, appropriate values of the impact crushing strength for particular ice types and conditions can be estimated only with a significant level of uncertainty. All available values are summarized in Table 1.

4. The impact crushing strength can be directly obtained from simple tests both in-situ and in laboratory conditions.
5. The effects of various testing conditions on the impact crushing strength are still mainly unclear. At the impact velocities ranging from 1 to 5m/s, the impact crushing strength appears to be almost velocity-independent, as follows from the data reported by Kheisin et al (1971, 1973), Khrapaty & Tsuprick (1976), Glen & Comfort (1983) and Sodhi & Morris (1986)—see Figures 2, 3 and 5. Some of the data sets from the two latter sources imply a velocity-dependence. However, a confident conclusion on this matter cannot be made from the data.

6. There is little data to trace the effect of indenter's mass and shape on the impact crushing strength. Kheisin's data of dropping two spheres with different masses (no sphere diameters are reported) in identical conditions imply that the mass effect is not great, if any. An indirect support for this conclusion can perhaps be made from comparing the data by Kheisin et al and Garcia et al. The masses used in both studies differed by two orders of magnitudes while the velocities were almost the same (from 1 to 5m/s in Kheisin's tests and 1.4 to 3.1 in Garcia's). The indenter shapes were different (sphere versus blunt cylinder) and their dimensions varied by two orders of magnitudes (somewhat exceeding 50cm in Kheisin's tests versus 6 and 11mm in Garcia's). In spite of the differences in the masses and shapes of both indenters, the values of the impact crushing strength obtained from both sources are very close to each other (see Table 1). On the other hand, the Garcia et al data (Fig. 4) imply a strong reciprocal dependence of the impact crushing strength on the impact energy. Given the energy in Garcia's tests varied within two orders of magnitudes and the velocity varied only from 1.4 to 3.1m/s, the masses could vary within at least one order of magnitudes. Thus, the energy-dependence may be attributed at least partly to the mass effect.

7. Data on temperature dependence, reported by Khrapary & Tsuprick for an unspecified sea ice and by Glen & Comfort for laboratory saline ice (Fig. 3), suggests a certain temperature effect but the qualitative estimates of the effect are different.

8. Only the data by Sodhi & Morris can provide some information on a relationship between the impact crushing strength and other strength characteristics, namely the bending strength of ice—see Fig. 5.

9. More experimental data is necessary to provide a designer with reliable data of the impact crushing strength of ice for various ice/structure impact scenarios and to correlate it to the compressive strength of ice.

**Acknowledgement**

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References


TABLE 1
EXPERIMENTAL DATA on IMPACT CRUSHING STRENGTH OF ICE "e"

<table>
<thead>
<tr>
<th>Ice type and conditions reported</th>
<th>e, MPa mean (st.dev.) [range]</th>
<th>Test type and data source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fresh-water ice cover, Ladoga Lake</td>
<td></td>
<td></td>
</tr>
<tr>
<td>January, (t_{air} = -30) to (-20)°C</td>
<td>9.8 (3.4)[4.7-26.9]</td>
<td>drop-ball</td>
</tr>
<tr>
<td>February, (t_{air} = -10) to (-5)°C</td>
<td>10.0 (1.9)[6.1-13.9]</td>
<td>Kheisin et al</td>
</tr>
<tr>
<td>February, (t_{air} = -22) to (-5)°C, c-axis horizontal</td>
<td>13.7 (2.7)</td>
<td>Kheisin et al</td>
</tr>
<tr>
<td>March, (t_{air} = +2) to (+4)°C</td>
<td>3.3 (0.8) [2-5]</td>
<td>- * -</td>
</tr>
<tr>
<td>Natural iceberg ice</td>
<td></td>
<td></td>
</tr>
<tr>
<td>in-situ, (t_{ice} = -6) to (-9)°C</td>
<td>16.4 (9.9) [2.5-34]</td>
<td>d/b, Johnson &amp; Benoit</td>
</tr>
<tr>
<td>laboratory samples, (t_{ice} = -5)°C</td>
<td>9.4 (2.7) [6.9-15.6]</td>
<td>d/w, El-Tahan et al</td>
</tr>
<tr>
<td>Natural sea ice cover</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Can. Arctic, Fox Channel, July, m.-y. ice</td>
<td>[4.5-6.2]</td>
<td>d/b, Pounder &amp; Little</td>
</tr>
<tr>
<td>Kara &amp; Laptev Seas</td>
<td></td>
<td>d/c, Dementyev</td>
</tr>
<tr>
<td>North Caspian Sea</td>
<td></td>
<td>d/w, Tsurikov et al</td>
</tr>
<tr>
<td>Antarctic ice</td>
<td></td>
<td>- * -</td>
</tr>
<tr>
<td>unspecified, (t_{ice} = -1) to (-14)°C</td>
<td>[2.2-19.4]</td>
<td>d/b, Kharapaty et al</td>
</tr>
<tr>
<td>Laboratory ice</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Artificial snow ice, (t_{ice} = -5)°C</td>
<td>15.4 (3.3) [9.8-22.1]</td>
<td>d/w, El-Tahan et al</td>
</tr>
<tr>
<td>Laboratory polycrystalline ice, (-5)°C</td>
<td>[1 to 35]</td>
<td>d/w, Garcia et al</td>
</tr>
<tr>
<td>Lab. saline ice, (-2) to (-25)°C; S=6, 1 ppt;</td>
<td>[0.4 to 6.0]</td>
<td>p., Glen &amp; Comfort</td>
</tr>
<tr>
<td>Laboratory urea ice</td>
<td></td>
<td>p., Sodhi &amp; Morris</td>
</tr>
<tr>
<td>Notations:</td>
<td>d/b = drop-ball, d/c = drop-cone, d/w = other drop-weight test, p = pendulum</td>
<td></td>
</tr>
</tbody>
</table>

Nomenclature

\(A; a_p\) - parameters of ice crushing strength
\(a\) - contact surface area
\(CR\) - restitution coefficient
\(D\) - diameter
\(E\) - total impact energy
\(E_C\) - impact crushing energy
\(F; F_{max}\) - instantaneous and maximum impact forces
\(g\) - gravity acceleration
\(h\) - height of dropping a weight
\(H\) - impact (dynamic) hardness
\(K_{sub}\) - numerical coefficients in eq. (7) and (12)
\(k\) - see equation (4)
\(L\) - length
\(M\) - mass
\(m\) - viscosity of crushed ice mass
\(P\) - instantaneous impact pressure
\(P_{av}\) - \(P\) averaged over contact area
\(F_{max,av}\) - \(F_{max}\) averaged over contact area
\(F_{max}\) - \(F_{max}\) maximum in time pressure at the center
\(r\) - cylindrical coordinate
\(r_0\) - imprint radius
\(R = D/2\) - radius of indenter
\(S\) - salinity
\(S\) - instantaneous time
\(T\) - impact duration
\(t\) - \(t_{air}\); \(t_i\) - temperatures of ambient air and ice
\(z\) - penetration depth
\(\alpha\) - \(E_{c}/E\)
\(\varepsilon\) - specific impact crushing energy
\(\rho\) - ice density

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Appendix: ICE LOADS FOR AXISYMMETRIC IMPACT

The indenters whose generatrix can be expressed by a single-term power function are being considered (Fig. 6):

\[ r = Sz^c \]

(A1)

For parabolic and conical indenters eq. (A1) is accurate, while for other shapes, e.g. for spherical and elliptical, the approximation (A1) may be used only for shallow penetrations where \( Z \ll R \). Identifying the volume of crushed ice mass with the volume of the indenter up to the depth \( Z \), one can get:

\[ W = \pi \int_0^Z r^2 \, dz = \pi S^2 Z^{2c+1} / (2c+1) \]

(A2)

and hence

\[ \varepsilon = (2c+1) \, MV^2 / 2\pi S^2 Z^{2c+1} \]

(A3)

Substituting (A1) into (5) and (6), and integrating (6) with \( Z \) expressed via (A3), yields a relationship between \( A \) and \( \varepsilon \):

\[ A = K_A \left[ \varepsilon^{5c+2} / SM^2 V^{6c+1} \right]^{1/(4c+2)} \]

(A4)

\[ K_A = \left[ \frac{(10c+4)/(7\pi)}{2\pi/(2c+1)} \right]^{(5c+2)/(4c+2)} \]

\[ I_o \int_0^1 (1-x^2/b^2)^{1/4} \, dx \]

where

\( 0 \leq x \leq 1 \) - dimensionless variable, \( b \geq 1 \) - factor accounting for spalling at the crater edges. For drop-ball tests, Kheisin et al (1975) estimate its value approximately within a range \( b = 1.05 \) - 1.08. No experimental data on spalling is available from any source. Therefore, both the value of \( I \) and the coefficients containing \( I \) should be calibrated from experiments. Equation (4A) can be used for replacing \( A \) in the expressions for impact load parameters derived earlier (Tunik, 1984) for the axisymmetric impact. As a result, we get:

\[ P_{\text{MAX}} = K_p \varepsilon \]

(A5)

\[ F = K_p \left[ \varepsilon M^2 V^4 S^3 \right]^{1/(2c+1)} \]

(A6)

\[ Z = K_z \left( MV^2 / \varepsilon S^2 \right)^{1/(2c+1)} \]

(A7)

\[ T = K_T MV/F \]

(A8)

where

\[ K_p = \frac{c(2/7)^{4c+2}}{(6c+1)(12c+2)/7} \left[ \frac{5c+2}{8/7} Z^{6/7} / (2c+1) \right]^{1/(2c+1)} \]

\[ K_z = \left[ \frac{(2c+1)/2\pi}{2^{2/5}} \right]^{1/(2c+1)} \]

\[ K_T = t_o K_z K_F ; \quad t_o = \int_0^1 (1-x^2/2)^{1/4} \, dx \]

For the particular shapes of spherical and conical (with the apex angle \( 2\psi \)) indenters these expressions turn out to simple formulae:

Sphere (c=1/2; S=D1/2)

\[ P_{\text{MAX}} = 1.20 \varepsilon \]

Cone (c=1; S=tan\( \psi \))

\[ P_{\text{MAX}} = 1.094 \varepsilon \]

\[ F = 1.60 (\varepsilon MD)^{1/2} V \]

\[ F = 1.74 (\varepsilon M^2 S^4 V^4)^{1/3} \]

\[ Z = 0.564 (M/\varepsilon D)^{1/2} V \]

\[ Z = 0.782 (MV^2 / \varepsilon S^2)^{1/3} \]

\[ T = 1.515 MV/F \]

\[ T = 1.98 MV/F \]
A NUMERICAL MODEL OF WATER DROPLET TRAJECTORIES

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ABSTRACT

A numerical model which simulates water droplet trajectories near and around a structure and some preliminary results are presented. The model has two main components; a hydrodynamical part that gives the flow field and a particle trajectory model. The hydrodynamical model includes a two equation turbulence model.

The model is used to compute the flow field around a rectangular obstacle. The trajectories for a range of water droplet diameters are calculated and shown.

1. INTRODUCTION

Icing on submerged structures and structures above the water line and on land is a well known problem in regions with cold climate. The present paper describes the basic formulation and some preliminary results of a mathematical model, which simulates particles trajectories in fluid flows.

The numerical model has been developed and used for simulating the freezeup due to frazil ice of a trash rack water intake to a hydro power station (Svensson and Andersson, 1988). In fact, if the flow field is known, it is possible to calculate the particle trajectories near and around a structure, and determine if the particles will collide with an obstacle or just pass by. In the present study the model is used to determine water droplet
trajectories in the atmosphere. It is expected that the droplets immediately freeze if they hit a cold structure or a power line. The mathematical model has two main components; a hydrodynamical model that gives the flow field, and the particle trajectory model. In most models of atmospheric icing it is assumed that there is a potential flow around an obstacle (Langmuir and Blodgett, 1946, Lozowski and Oleskiw, 1983, Makonen and Stallabrass, 1987, Finstad and Lozowski, 1988) but the present study recent advances in computational fluid dynamics is utilized. Thus the flow field is determined from the basic momentum equations and a two-equation turbulence model. This approach open new possibilities to study, for example, the effect of free stream turbulence on the particle trajectories in the wake of the obstacle. The particle trajectory model is essentially the same as has been used by Lozowski and Oleskiw (1983). In the present paper the emphasize is on the fluid and particle dynamics. Thus, collision efficiency, thermodynamics of the surface, accretion shape, etc are not considered.

2. MATHEMATICAL MODEL

The momentum equations for the continuous phase, or the carrier phase, are formulated assuming that no buoyancy forces are present, the fluid is incompressible, the turbulent transport can be described by the eddy-viscosity concept and that the momentum source from the particles can be neglected. It also assumed that the volume occupied by the droplets may be neglected when the continuous phase is considered.

The equation of motion for a particle is based on a drag-law formulation, with a Reynolds-number dependent drag coefficient. No exchange of heat or mass between the particle, in this case the droplet, and the fluid is considered. The size of the droplet will not increase or decrease.

The turbulence field is described with a two-equation turbulence model, the k-ε model, see Rodi (1980). The presence of the droplets is considered not to affect the turbulence conditions.

With these assumptions the following set of equations can be formulated:
Continuous phase

Momentum:
\[
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = -\frac{1}{\rho} \frac{\partial p}{\partial x} + \frac{\partial}{\partial x} \left( u_T \frac{\partial u}{\partial x} \right) + \frac{\partial}{\partial y} \left( u_T \frac{\partial u}{\partial y} \right) \tag{1}
\]
\[
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = -\frac{1}{\rho} \frac{\partial p}{\partial y} + \frac{\partial}{\partial x} \left( u_T \frac{\partial v}{\partial x} \right) + \frac{\partial}{\partial y} \left( u_T \frac{\partial v}{\partial y} \right) \tag{2}
\]

Continuity:
\[
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{3}
\]

Turbulence model:
\[
\frac{\partial u_k}{\partial x} + \frac{\partial v_k}{\partial y} = \frac{\partial}{\partial x} \left( u_T \frac{\partial k}{\partial x} \right) + \frac{\partial}{\partial y} \left( u_T \frac{\partial k}{\partial y} \right) + G - \varepsilon \tag{4}
\]
\[
\frac{\partial u_e}{\partial x} + \frac{\partial v_e}{\partial y} = \frac{\partial}{\partial x} \left( u_T \frac{\partial e}{\partial x} \right) + \frac{\partial}{\partial y} \left( u_T \frac{\partial e}{\partial y} \right) + \frac{\varepsilon}{k} \left( C_{1e} G - C_{2e} \varepsilon \right) \tag{5}
\]
\[
G = u_T \left[ 2 \left( \frac{\partial u}{\partial x} \right)^2 + 2 \left( \frac{\partial v}{\partial y} \right)^2 + \left( \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right)^2 \right] \tag{6}
\]
\[
u_T = \frac{C_\mu k^2}{\varepsilon} \tag{7}
\]

where \( u \) and \( v \) are velocities, \( p \) pressure, \( \rho \) density, \( u_T \) kinematic eddy viscosity, \( k \) turbulent kinetic energy, \( \varepsilon \) dissipation rate of \( k \) and \( G \) generation due to shear. The coordinate system is denoted by \( x \) and \( y \), see Figure 1. Constants in the turbulence model are given as: \( C_\mu = 0.09 \), \( \alpha_k = 1.0 \), \( \alpha_e = 1.3 \), \( C_{1e} = 1.44 \) and \( C_{2e} = 1.92 \).

Particle equations

Momentum:
\[
\frac{d u_p}{d t} = \frac{1}{2} C_D \rho_p \frac{d^2}{d x^2} |u - u_p|(u - u_p) \tag{8}
\]
\[
\frac{d v_p}{d t} = \frac{1}{2} C_D \rho_p \frac{d^2}{d y^2} |v - v_p|(v - v_p) \tag{9}
\]
Drag-law:
\[ C_D = \frac{24}{Re_p} (1 + 0.15 \frac{Re_p}{0.687}) \]  

(10)

where \( m \) is the mass of the particle, \( \rho_p \) its density and \( d \) the diameter.
Particle velocities are denoted by \( u_p \) and \( v_p \). The drag-coefficient is denoted \( C_D \) and \( Re_p \) is a particle Reynolds number (Wallis, 1969).

Other aerodynamic forces acting on a water droplet, due to pressure gradients, added mass and Basset term are neglected because the density ratio between air and water is of the order 0.001. The air velocity is steady over the particle time integration.

It should be noted that the equations for the continuous phase are formulated in an Eulerian framework, while the particle equations represent a Lagrangian approach. This explains the time derivative in equations (8) and (9), as the particle can experience acceleration, even though the mean flow field is steady, if the observer moves with the particle.

\[ x_{\text{new}} = x_{\text{old}} + \Delta t \left( u_{\text{old}} + u_{\text{new}} \right)/2 \]

(11)

where \( \Delta t \) is the time increment.

3. RESULTS

The situation considered is schematically shown in Figure 1. Due to symmetry conditions the computational domain can be restricted to half a bar and half the space between the bars. The wake behind the bar is not considered so the computational domain ends before this region. At the inlet a uniform velocity is prescribed.
The predicted velocity field is shown in Figure 2, where also the computational grid can be found. The result is according to expectations, with a recirculation zone on the side of the bar. The corresponding pressure (Pa) and kinematic eddy viscosity (m$^2$/s) fields are shown in Figure 3. Zero pressure was prescribed at the outlet boundary and the pressure field shown is thus the pressure with reference to this boundary. The highest pressure is found at the stagnation point on the forward facing part of the bar, while the minimum pressure is to be found on the side of the bar. The kinematic eddy viscosity distribution shows a maximum in the region of high shear which seems reasonable. It can be understood from the figure that the prescribed free stream turbulence level is fairly low. The turbulence properties at the inflow boundary were in fact chosen to be similar to the turbulence generated at the obstacle. The rational behind this is that only the turbulence that has a length and time scale comparable to the time and length scale of the flow around the obstacle will have any influence. The "passage time" for the flow (L/u) is of the order 0.001 s so the large scale atmospheric turbulence is not the correct free stream turbulence level to be used.

Computed droplet trajectories for three different droplet diameters (1.0, 5.0 and 15.0 μm) are shown in Figure 4. The density of the spherical droplets was set to 1000 kg/m$^3$. Seven droplets were released at the inlet and then allowed to travel through the domain. The main result from Figure 4 is that the largest droplets (d = 15.0 μm) have enough inertia to cross the flow field while the smallest droplets (d = 1.0 μm) will follow the flow field almost like a tracer.
Figure 2. Computational grid and predicted velocity field.
Figure 3. Pressure and kinematic eddy viscosity fields.
Figure 4. Water droplet trajectories for three droplet diameters.
4. DISCUSSION AND FUTURE WORK

The predictions presented represent a first attempt to simulate a water droplet impinging on a structure. The results seem plausible but quantitative verification studies are needed to put the predictions on a firm ground. The simulations are compared with exact analytical solutions for simple cases like acceleration of a particle in a uniform flow field, but not reported in present paper. Good agreement was obtained which shows that the basic formulation and the coding are correct. However, one also needs to verify that the flow field around the bar is correctly obtained which calls for comparisons with laboratory measurements carried out in a wind tunnel.

Different from these verification studies are improvements in the mathematical formulation. One such possible improvement, that we are going to investigate, deals with the influence of the turbulence on the particle trajectory. Recently, see Walklate (1987), the Markov-chain technique has been developed to include particles with inertia. It is especially tempting to evaluate this technique as the time scale for the turbulence, which is required in the formulation, can be obtained from the k-ε turbulence model. This has been shown by Rahm and Svensson (1986).

Improvements are also possible in terms of presentation and interpretation of results. As an example, one may generalize the results presented in Figure 4 by comparing the droplet relaxation time, defined as (Durst et al, 1984):

\[ \tau_p = \frac{4 \rho_p d^2}{3 \mu \frac{C_D}{\text{Re}_p}} \] (12)

with the characteristic flow time (\( \tau_f = \frac{L_{\text{obstacle}}}{u} \)). The droplet relaxation time gives the time scale for changing the velocity of the droplet while \( \tau_f \) can be interpreted as the time the droplet spends in the domain. For the three droplet diameters used for the simulations presented in Figure 4 the ratios \( \frac{\tau_p}{\tau_f} \) were 0.05 (d = 1.0 \( \mu \text{m} \)), 1.1 (d = 5.0 \( \mu \text{m} \)) and 8.4 (d = 15 \( \mu \text{m} \)). It is anticipated that non-dimensional representations of the results from simulation can be developed along these lines, which of course should be useful from a practical point of view.

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5. REFERENCES


STRENGTH AND DEFORMATION OF SPRAY ICE

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ABSTRACT

Exxon has conducted a spray ice mound field test program at the Orion drill site to the west of Harrison Bay in the Alaskan Beaufort Sea. In the program, vertical and horizontal displacements were measured to monitor the deformation of the spray ice mound subject to its own weight and ice loadings. Thermistors were installed to measure in-situ temperature and cone penetrometer tests were conducted to determine the uniformity of spray ice composition. In addition, spray ice cores were taken and strength tests were conducted at the site. This paper describes the field operations and presents the results from the instrumentation and strength tests. Other specific results obtained from Exxon programs in McKinley Bay in the Canadian Beaufort Sea and at the Antares drill site near the Orion site are also summarized for comparison.

1. INTRODUCTION

Interest in spray ice platforms for exploration drilling in the Beaufort Sea increased after the successful performance of spray ice drilling platforms at Amoco's Mars drill site and Esso Resources Canada's (ERC) Angasak drill site [1, 2]. Both Amoco and ERC used a "layer-by-layer" method of spray ice accumulation, with careful monitoring of ice properties during construction. Exxon deployed the Concrete Island Drilling System (CIDS) for exploration drilling at the Antares site during the winter of 1984/85. A much more rapid construction method, "continuous spraying," was used to construct a spray ice barrier around the CIDS to add extra protection from ice loading [3]. With this rapid construction method and appropriate design configurations [4], spray ice platforms may be used satisfactorily in water depths up to and beyond 30 ft (9 m).

Limited information on the strength of spray ice has been published; however, most of the published data pertain to above-water spray ice or remolded spray ice samples [5, 6]. In order to determine the properties of undisturbed under-water spray ice, Exxon conducted a spray ice field test program at the Orion drill site during the winter of 1985/86. This paper describes the field operations and presents the strength and deformation data obtained. Previous Exxon experience with spray ice has been reported in Reference 3. Specific ice property results from those programs are summarized for comparison.
2. FIELD OPERATIONS

The Orion drill site was at a 50-ft (15-m) water depth location approximately 12 miles (19 km) offshore northeast of Cape Halkett (Figure 1). A spray ice mound with a peak freeboard approximately 50-ft (15-m) high was constructed to the west of the CIDS at the end of January 1986 for the test program. At the end of February, an area approximately 50-ft by 90-ft (15-m by 27-m) in the saddle region of the mound was leveled to 46 ± 0.5 ft elevation. A 50-ft by 50-ft (15-m by 15-m) test site inside the leveled area was selected for instrumentation and testing.

Several strings of instruments were installed in holes drilled through the thickness of the spray mound and into the seafloor. The instrumentation installed in the test area included: one Sondex tube and one thermistor string near the center; four additional Sondex tubes, one near each corner of the test area; and one inclinometer casing about 20 ft (6 m) east of the southeast corner of the test area. Brand names of some products are used in this paper for the ease of discussion. Any products with equivalent utilities could also be used. Periodic data measurements from these instruments were taken manually until the end of May. At that time, the test area remained flat without visual evidence of differential settlement or other disturbances. The ice surface was still firm and frozen. A number of topographic surveys were also conducted to document surface subsidence of the spray ice mound. During the period February 2 to May 21, six topographic surveys were conducted. The elevation contour map from the February 26 survey is shown in Figure 2.

A geotechnical testing program was conducted during March. Seven cone penetrometer test (CPT) logs were obtained: two at the center, one at each of the four corners, plus an additional test at the southeast corner. A wireline-retrievable core barrel and a CO₂ freezing sampler were employed to retrieve undisturbed cores of below-water spray ice. The wireline core barrel, which latched inside a hollow-stem auger, was generally more successful; recovery was more than 95 percent in the above-water ice, and 85 percent below water level. However, the coring auger for the wireline method was damaged after completion of the first hole; therefore, the much slower CO₂ freezing method was used for the second core hole. The CO₂ device was a thick-walled push sampler designed to rapidly freeze the outer edges of a slushy ice sample in order to hold the sample in during retrieval. With the CO₂ coring method, recovery was less reliable and resulted in more disturbed (compacted) cores.

The Orion site data are comparable to the results obtained from two spray ice research projects conducted by Exxon previously. At the McKinley Bay barrier test site in February-March 1984, above- and below-water cores were obtained. Two drilling programs were conducted in the Antares spray ice barrier during the period February-May 1985. In the first Antares program, surficial cores and below-water auger cuttings were obtained for testing. In the second Antares program, below-water samples were obtained for visual inspection and logging, and CPT tests were conducted [3].

Strength tests conducted at the Orion site included triaxial compression tests and double-direct shear tests on both undisturbed and remolded samples. Sample testing was conducted in an instrument trailer at the base of the Orion test mound. The air temperature in the portion of the laboratory where triaxial testing was conducted was controlled to between 0°C and -2°C. The setup of the triaxial test machine was essentially the same as that described in Reference 5. A temperature control system consisting of a circulating antifreeze/brine bath controlled the test temperature to within 0.1°C. In the outer portion of
the laboratory where the direct shear tests were conducted, the
temperature varied between about +3°C to -10°C.

3. SUBSIDENCE

Surface subsidence, caused by time-dependent deformation of the spray
ice mass, is one of the critical aspects of spray ice drilling platform
performance. The anticipated total and differential settlements are of
particular interest for rig foundations.

3.1 Topographic Surveys.

The overall settlement pattern of the spray mound is shown in Figure 3
by contouring elevation differences between the February 26 and May 21
surveys. This survey span might be considered to be the nominal
operational period of a spray ice platform constructed in January.
During this time period, the leveled test area settled by about 3.8 ft
(1.2 m) and the maximum differential settlement between any of the five
Sondex sites was only about 4.0 inches (10 cm) (Figure 4a). The rate of
settlement decreased with time. Note that the settlement contours have a
shape similar to the elevation contours in Figure 2. This suggests that
surface settlement is correlated with the thickness of the underlying
spray ice mass, as would be expected.

3.2 Sondex Measurements

Surface settlements based on the Sondex measurements are given in Fig­
ure 4b for comparison. The initial readings were obtained on March 21,
immediately after installation of these instruments. The Sondex readings
for the period March 21 to May 21 show an average settlement of 2.2 ft
(0.67 m). This agrees well with an average settlement for the test area
of 2.1 ft (0.64 m) between April 8 and May 21 as determined from
topographic surveys. Maximum differential settlement across the pad
based on Sondex data for the period March 21 to May 21 was about 1.5
inches (3.8 cm). The settlement values derived from Sondex measurements
are probably more accurate than the survey data because it was not always
possible to identify the exact same points for repeated survey measure­
ments.

Settlement profiles, as measured by a typical Sondex probe, are
reproduced in Figure 5. The slope of these profiles is somewhat steeper
below water than above, consistent with similar measurements obtained at
the Antares spray ice barrier. Using a bi-linear fit to the observed
data, it is estimated that the vertical strain in the saturated underwa­
ter ice was about twice that of the unsaturated ice above water level.

4. LATERAL DISPLACEMENTS

Topographic survey data indicate that the test mound underwent lateral
deformations, presumably in response to loads imposed by the surrounding
ice sheet. This is evident from Figure 6, where "initial" and "end"
positions of the survey markers are plotted for the time periods April 8
to May 21. Displacement in the central mound area was about 1.5 ft (0.5
m) directed towards the north-northwest.

Evidence of lateral displacement is supported by data from the
inclinometer string (Figure 7) that was installed on March 21. The
largest deformation is evident from a comparison of the profiles measured
on April 8 and May 2. Shear deformation of about 6 inches (15 cm)
ocurred in the lower part of the string, which extended several feet
into the soil. Comparing this value with the survey measurements of
about 1.5 ft (0.5 m), it appears that the lower end of the inclinometer
string must have been dragged through the soft surficial sediments in
addition to being deformed. Therefore, we conclude that most of the lateral displacement measured at the surface was due to sliding of the spray mound on the seafloor. A small amount of creep deformation may also have occurred within the spray ice itself.

5. STRENGTH
5.1 CPT Logs

A tip resistance profile for one typical site is reproduced in Figure 8. All the profiles indicated considerable uniformity compared to previous data from the Antares spray ice barrier [3]. (The spikes at 1-m intervals are the result of signal interruption during addition of cone rod extension sections.) This uniformity may be due to the fact that construction was nearly continuous and that spraying was concentrated in a small area. The rapid, continuous ice accumulation without intermittent curing periods resulted in a notable absence of layering. A hard layer, which is interpreted to be the submerged layer of natural sea ice on which the spray ice was initially deposited, is evident above the mudline, as is also the case in the Antares profile [3]. Just above this hard layer is typically a weak zone that may be due to an accumulation of brine which drains from the porous spray ice. The CPT is typically used only to evaluate the uniformity of the spray ice deposit, rather than as a strength measure, due to the lack of applicable strength correlations and rate-dependent or bonding-dependent behavioral models. No development work in this area was undertaken in this program.

5.2 Core Inspection

An interpreted through-thickness log of the Orion spray ice mound is shown in Figure 8. Visual inspection of the core samples revealed four distinct ice zones: 1) hard-frozen spray ice near the surface (frozen crust); 2) drained above-water spray ice consisting of interbedded bonded and unbonded (powdery) layers; 3) saturated under-water spray ice, normally slightly bonded, but with 30-40 percent unbonded slush ice; and 4) hard annual sea ice directly above the seafloor. This profile is similar to the findings at the Antares location [3]. The core samples were classified by the apparent bonding into four groups: bonded, moderately bonded, moderately soft, and soft. A sieve analysis conducted on an unsaturated sample indicated the following grain-sized distribution: 28%, .025-.05 inches (.63-1.3 mm); 72%, 0.013-0.025 inches (0.32-0.63 mm). Visual inspection of saturated samples indicated a grain-size range of 0.02-0.08 inches (0.5-2.0 mm), with an average of about 0.04 inches (1.0 mm).

Core samples were kept sealed in the 3.3-inch (84-mm) diameter PVC core barrel liners after drilling until the samples were extruded for testing in the field laboratory. The sealed sample tubes for the below-water cores were kept in barrels filled with seawater that were thermally stable at near the freezing point of the seawater, and above-water cores were stored in a freezer at -5°C ± 1.5°C. Some cracks due to drilling or sample handling and some minor freezing were evident upon core extrusion, but most cores had undisturbed portions large enough for testing. Remolded samples were formed in a 2.8-inch (72-mm) diameter split mold in lightly-tamped lifts.

5.3 Strength Tests

Strength tests included 43 triaxial compression tests (34 on undisturbed samples) and 32 double direct shear tests (30 on undisturbed samples). Both consolidated-drained and consolidated-undrained (with pore pressure measurement) triaxial tests were conducted. After mounting in the triaxial cell, below-water samples were backsaturated with
seawater brine (about 35 parts per thousand). Above-water samples were not saturated. The samples were isotropically consolidated using net confining pressures ranging from 0.4 to 1.7 ksf (20 to 80 kPa) for the above-water samples, and from 0.8 to 3.9 ksf (40 to 185 kPa) for the below-water samples.

Triaxial tests on below-water samples were primarily undrained tests but some below-water samples, as well as all above-water samples, were tested under drained conditions. Most of the tests were conducted at an axial strain rate of about 5x10^-5 sec^-1; axial strain rates ranged from 3.3x10^-8 to 7.8x10^-5 sec^-1 for the below-water samples, and ranged from 1.3x10^-5 to 2.9x10^-4 sec^-1 for the above-water samples. At the average strain rate, each triaxial test took about one hour to complete.

5.4 Triaxial Test Results

A simple model of spray ice strength behavior was desired. The model selected was a Mohr-Coulomb effective stress model, typical of those used in soil mechanics. However, other models could have been used. In the effective stress model, the failure envelope is represented by a straight line on a plot of shear effective stress ("q") versus mean normal effective stress ("p'"). The failure envelope can also be defined in terms of the Mohr-Coulomb equation

\[ \tau = c + \sigma \tan \phi \]  

where \( \tau \) = shear strength, \( c \) = effective cohesion, \( \sigma \) = normal or overburden stress, and \( \phi \) = effective friction angle. As discussed below, the below-water, saturated spray ice results fit this model well, but the above-water spray ice results required a different definition of the failure point in order to fit the same model. Therefore, the strength results reported are referred to as "interpreted" shear strengths.

Interpreted shear strengths for the samples tested in the triaxial machine ranged from 4 to 8 ksf (190-380 kPa) for the above-water ice. The above-water strengths varied approximately linearly with depth from the ice mound surface (Figure 8), as would be expected from the linearly increasing in situ overburden pressure. Below-water strengths were much more variable: the more bonded below-water ice samples had strengths in the 3.5 to 6.5 ksf (170-310 kPa) range, while the unbonded samples were in the 2 to 3.5 ksf (95-170 kPa) range. The vertical stress under a drilling rig is generally less than 2 ksf (95 kPa).

Figures 9a and 9b show envelopes of stress-strain curves for unsaturated, above-water samples and for saturated, below-water samples (grouped by bonding classification), respectively. The stress-strain curves from the triaxial tests for the above-water samples and the more bonded below-water samples are distinctly bi-linear in appearance. The bonded spray ice appears to "yield" (exhibit a significant decrease in the slope of the stress-strain curve) at about two percent strain. The "yield" point was used as the basis for the interpreted shear strength of the bonded above-water spray ice.

For the softer below-water samples, the stress-strain curves are much more rounded and indicate that the unbonded material experiences larger deformations prior to reaching the interpreted shear strength. The below-water spray ice, both bonded and unbonded, also appears to begin its nonlinear behavior at about two percent strain. However, in most tests on below-water, saturated spray ice, the "failure" point, defined as the point at which the q/p' ratio is a maximum, was out on the flat part of the stress-strain curve. The "failure" point was used as the basis for the interpreted shear strength for saturated samples. The locus of failure points for saturated below-water ice gives the effective stress parameters \( \phi = 51.5^\circ \) and c=0.24 ksf (11.5 kPa). The saturated test
results reported in [5] are generally consistent with this failure envelope, but the consolidation stress range of that study was too small (0.4-1.2 ksf, 20-60 kPa) to draw definite conclusions.

As seen in Figure 10, the "yield" stress condition for the unsaturated, above-water samples appears to be consistent with the "failure" envelope inferred from the saturated, below-water samples. It may be that the intergranular processes governing the failure of the saturated samples also control the yielding of the unsaturated samples. Therefore, it appears appropriate to use the same effective stress envelope to estimate design shear strength for both types of spray ice.

The stress-strain behavior of the spray ice, both saturated and unsaturated, is not greatly affected by confining pressure, strain rate, or temperature within the ranges tested. Remolded samples, which are comparable in strength to the softer undisturbed saturated samples, exhibit increased strength and a more distinct yield point when allowed to consolidate for a longer period of time (six hours versus the "standard" one hour) or tested at a lower temperature (-2.5°C versus the "standard" -1.5°C).

5.5 Direct Shear Results

Double-direct shear tests were conducted on both above- and below-water samples. With a double-direct shear device, shearing across two parallel planes is accomplished by pulling at a constant rate a containing ring around the middle one-third of the sample relative to fixed rings around the top and bottom sample sections. Vertical load on the sample is applied using a hanging-weight system. As shown in Figure 11, the results for remolded samples and some of the softer samples of saturated spray ice are consistent with the effective stress failure envelope for the saturated sample triaxial tests. Also shown for comparison in Figure 11 are results from the Antares testing program, which used a similar double-direct shear device, and results from the McKinley Bay program, which used a standard (two moving boxes) direct shear device. Both of these two sets of data were from testing of remolded below-water spray ice, and the results are also consistent with the effective stress failure envelope. The high strengths measured in the Orion program may have been due to unobserved differences in internal bonding or an unknown stress state caused by tilting of the vertical load at large strains.

6. SECONDARY TESTING

A number of secondary tests were performed on the spray ice samples. These tests included density and salinity measurements, as shown on Figure 8. Sample densities were about 34 to 40 pcf (0.55-0.65 gm/cm³) above water, increasing with depth below the mound surface, and about 51 to 57 pcf (0.82-0.92 gm/cm³) below water. It is likely that the below-water density measurements were somewhat low due to brine drainage during sample retrieval and handling. The above-water spray ice was almost non-saline with a typical bulk salinity of one part per thousand (ppt) or less. Salinity ranged from 10 to 14 ppt for below-water ice, and from 36 to 37 ppt for brine drained from below-water ice samples.

7. TEMPERATURES

Temperature profiles measured by the thermistor string at the center of the test area and measured from ice cores are shown in Figure 8. While later thermistor temperature profiles taken on May 1 and May 21 show significant warming near the ice surface, the bulk of the above-water spray ice remained well below the freezing point. Temperatures of the below-water spray ice averaged about -2.1°C (28.2°F).
8. CONCLUSIONS

The following specific conclusions have been drawn from field observations and analysis of data collected during the Orion Spray Ice Mound test:

- Strength and deformation data indicate that spray ice deposited by continuous spraying has adequate foundation strength for spray ice drilling platforms.
- A curing period of up to one month is desirable to allow for consolidation and initial settlement of the spray mound prior to leveling and rig setup.
- Consolidation and surface settlement will continue at a moderate rate, on the order of 1 ft (0.3 m) per month, during the useful lifetime of the spray ice platform.
- Differential settlement between various points on the drilling platform is expected to be only a few inches, assuming generally uniform ice conditions.
- Failure strengths of the spray ice material are predictable using a Mohr-Coulomb model. Significant nonlinear deformation occurs beyond about 2 percent strain.

9. ACKNOWLEDGEMENT

The authors gratefully acknowledge Golder Associates and Foundex Explorations Ltd. for undertaking the field program, and L. B. Blanton, H. O. Jahns, D. H. Petrie, J. P. Poplin, and other personnel from Exxon Production Research Company who participated in different phases of the project. Personnel from Global Marine Drilling Company and Exxon Company, USA at the Orion site were also most helpful in the execution of the field work.

10. REFERENCES

FIG. 1. LOCATION MAP

FIG. 2. FEBRUARY 26 ELEVATION CONTOUR MAP

FIG. 3. INCREMENTAL SETTLEMENT FEBRUARY 26 TO MAY 21
FIG. 4a. ELEVATIONS AS MEASURED BY SURVEY

FIG. 4b. ELEVATIONS AS MEASURED BY SONDEX

FIG. 5. SETTLEMENT PROFILES MEASURED BY SONDEX
1.3 Z5 ELEVATION AND DISPLACEMENTS IN FEET

SURVEY GRID - 4/8
SURVEY GRID - 5/21

FIG. 6. LATERAL DISPLACEMENTS AS MEASURED BY SURVEY - APRIL 8 TO MAY 21

FIG. 7. INCLINOMETER DATA
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* THERMISTOR READINGS
* CORE TEMPERATURES
* TRIAXIAL TEST SAMPLES
* DOUBLE DIRECT SHEAR TEST SAMPLES
* UNDISTURBED CORE SAMPLES
* TRIAXIAL TEST RESULT
* DOUBLE DIRECT SHEAR TEST RESULTS

FIG 8 BOREHOLE 1 STRATIGRAPHY AND TEST RESULTS
FIG. 9a. STRESS-STRAIN CURVE ENVELOPE FOR UNSATURATED, ABOVE-WATER SPRAY ICE

NOTE: DEVIATOR STRESS = $\sigma_1 - \sigma_3$

FIG. 9b. STRESS-STRAIN CURVE ENVELOPES FOR SATURATED, BELOW-WATER SPRAY ICE

NOTE: DEVIATOR STRESS = $\sigma_1 - \sigma_3$
FIG. 10. EFFECTIVE STRESS STATES AT FAILURE

$\sigma' = \frac{\sigma_1 + \sigma_3}{2}$

$q = \frac{\sigma_1 - \sigma_3}{2}$

$\sigma' = 115 \text{ kPa} = 24 \text{ ksf}$

$\phi' = 51.5^\circ$

FIG. 11. DOUBLE DIRECT SHEAR TEST RESULTS
NUMERICAL MODELLING OF

SEA SPRAY ICING ON VESSELS.

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ABSTRACT

A time-dependent numerical model of sea spray icing with special application for ships is presented. The model has been used to calculate icing on various test objects attached to the front mast of the observation vessel "Endre Dyrøy" when operating in the Barents Sea. A new calibrated formula of spray mass flux was used as input to the model. This formula is based on spray collector measurements, also at the front mast of "Endre Dyrøy". The correlation between measured and computed ice thicknesses was rather satisfactory.

NOMENCLATURE

\( C \) = specific heat capacity (J/kg°C) or wave velocity (m/s)
\( U \) = unit heat flux (W/m²)
\( f \) = relative humidity
\( L_i \) = specific latent heat of fusion of pure ice (J/kg)
\( S \) = salinity (parts per thousand)
\( W \) = vessel speed (m/s)
\( \mathbf{v} \) = velocity vector (m/s)
\( U \) = free wind velocity (m/s)
\( \mathbf{v}_s \) = \((V_x, W_z)\) spray bulk velocity vector upon impact with components in horizontal and vertical direction (m/s)
\( \mathbf{k} \) = unit vector in vertical direction
\( g \) = acceleration of free fall (m/s²)
\( G \) = free stream mass flux of spray per unit area (kg/m²s)
\( R_L \) = local water catch rate of impinging spray (kg/m²s)
\( R \) = local icing intensity (kg/m²s)
\( E \) = energy flux per unit length (W/m)
\( L \) = time-average liquid water content in the spray (kg/m³)
\( \dot{m} \) = mass transfer rate (kg/m²s)
\( M \) = total mass of ice or spray (kg)
\( N \) = spray frequency (s⁻¹)
\( H \) = wave height (m)
\( T \) = wave period, or time interval of spraying or icing
\( t_s \) = duration of a single spray (s)
\( \lambda \) = wave length (m)
1. INTRODUCTION.

We may distinguish between empirical and numerical icing simulation models. To the first category belongs nomograms, showing the icing rate as a function of wind speed, air temperature and sea surface temperature (Mertins, 1968) or only wind speed and the air temperature (Sawada, 1966; Lundquist and Udin, 1977; Stalabrass, 1980; Pease and Comiskey, 1985).

The other approach to icing estimations is by using physical or numerical models such as those of Stalabrass (1980), Makkonen (1985), Horjen and Vefsnmo (1986 I) and Zakrzewski (1986). A common feature of these models is that all the environmental parameters such as spray flux, air temperature etc. are assumed constant.

The theory of time-dependent icing due to a spray flux changing in time, i.e. collision-generated spray, was originally developed some years ago as part of the "Offshore Icing" program at the Norwegian Hydrotechnical Laboratory (Horjen and Vefsnmo, 1986 I, 1987). An overview of the new model was presented at the previous POAC conference in Fairbanks (Vefsnmo et al. 1987). During the last years the model has been further refined and the final version, especially developed for ships, is presented in this paper.

The objective of the "Offshore Icing" program was primarily to investigate ice accretion on drilling rigs; however, one of the sub-projects was icing hazards on supply and stand-by vessels (Horjen et al. 1986). As a part of this project spray characteristics were measured on three supply vessels and the observation ship "Endre Dyrøy". Additionally ice thicknesses were recorded on the latter ship at the onboard location where sea spray measurements took place. This is therefore a most valuable set of data for model evaluation. During the icing observations the position of "Endre Dyrøy" was about 74° North in the Barents Sea.
2. THE EQUATIONS OF TIME-DEPENDENT SEA SPRAY ICING.

The sea spray icing model is based on the equations of conservation of mass, heat energy and salt content in the brine film covering the ice surface during "wet growth". They have the following form (Højen and Vefsnmo, 1986 II):

\[
\frac{\partial (\rho \delta)}{\partial t} + \nabla \cdot (\rho \delta \mathbf{v}_s) = R_m + \dot{m}_s - R \quad (2.1)
\]

\[
\frac{\partial D_s}{\partial t} = \dot{\Omega}_s + (1-\sigma) l_i + \dot{\Omega}_s \quad (2.2)
\]

\[
\frac{\partial \rho}{\partial t} = R_s \delta - S_1 (R_m + \dot{m}_s - R(1-\sigma)) \quad (2.3)
\]

where

\[
D(\cdot) = \frac{\partial (\cdot)}{\partial t} + \mathbf{v}_s \cdot \nabla (\cdot)
\]

\(\sigma\) is the liquid water fraction in the ice layer adjacent to the surface film (For a brine film this is the same as the "interfacial distribution coefficient" \(S_1 / S_1\)). In the model we assume \(\sigma\) to be independent of icing conditions. For saline water spray a mean value of 0.34 was obtained from Japanese field data, and Finnish and Russian wind tunnel data (Vefsnmo et al., 1987).

3. SEA SPRAY CHARACTERISTICS FOR VESSELS WITH SPECIAL ADJUSTMENTS TO THE "ENDRE DYRøY" MEASUREMENTS.

3.1 The spray impingement angle.

Consider a ship moving at a speed \(W\). In an absolute reference system the heading of waves relative to the propagation direction of the ship is \(\alpha\). If the icing object is vertical we define \(\gamma\) to be the angle between its horizontal axis and the ship's propagation direction (see Fig. 3.1). We assume that wind and spray are coming from the same direction as the waves.

The horizontal vector component of the spray bulk velocity may be expressed by:

\[
\mathbf{V}_s = k \times (\mathbf{V}_s \times k) \quad \text{(absolute system)} \quad (3.1)
\]

\[
\mathbf{V}_{s,r} = k \times ((\mathbf{V}_s - \mathbf{W}) \times k) \quad \text{(relative system)} \quad (3.2)
\]

Using these relations the spray heading in the relative system becomes

\[
\alpha_r = \pi - \arccos \left( \frac{\mathbf{V}_{s,r} \cdot \mathbf{W}}{V_s W} \right) = \pi - \arccos \left( \frac{\mathbf{V}_s \cdot W - W^2}{V_s W} \right)
\]

or
\[ \alpha_r = \arccos \left( \frac{V_i}{V_{ir}} \cos \alpha + \frac{W}{V_{ir}} \right) \]  \hspace{1cm} (3.3)

where

\[ V_{ir} = \left| \vec{V}_{ir} \right| = \left| \vec{V}_i - \vec{W} \right| = \left( V_i + W + 2 V_i \cdot W \right)^{\frac{1}{2}} \]

Unless the droplet flight distance is very short the horizontal component of the spray bulk velocity in the absolute reference system is approximately equal to the wind velocity. We may now calculate the impingement angle in the relative system from

\[ \psi_r = \pi - (\alpha_r + \gamma) \]  \hspace{1cm} (3.4)

Both the heat transfer coefficient (Horjen and Vefsnmo, 1987) and the local water catch rate \( R_w \) for a vertical plate depend on this parameter.

---

3.2 Spray mass flux.

Using some simple physical arguments we will try to find a formula for the spray flux generated by a moving vessel. We shall use the following hypothesis:

1. The vertical energy flux per unit width and wave length of spray droplets near the sea surface (\( z = H_s/2 \)) is proportional to the energy flux per unit width of significant waves colliding with the ship.
2. The liquid water content (LWC) of descending spray at some level $z \leq H_s/2$ is proportional to the LWC near the sea surface and a power function of $(z - H_s/2)$.

From linear wave theory the energy per unit width of significant waves approaching the ship per unit time is given by

$$E_s = \frac{1}{8} \rho_w g H_s^{-2} \left( C_n + W \cos \alpha \right)$$

where $C_n$ is the group velocity which for large depths is about half the phase velocity. The mean energy flux of spray droplets per unit width and wave length of the sea surface may be expressed by

$$E_r = \frac{1}{2} \bar{\lambda}_s L(H_s/2) W_s$$

where the bar denotes the mean value over the distance $\lambda_s$.

Using droplet kinematics and dimensional analysis an expression of the droplet ejection velocity may be found which is proportional to the free wind velocity $U$ (Horjen and Vefsnmo, 1985). Although a trajectory model probably is not the best way of analyzing spray distribution this conclusion seems to be likely and will be adapted here. From the first hypothesis we now have

$$L(H_s/2) \propto \left( \rho_w g H_s^{-2}/\lambda_s^2 \right) \cdot \left( C_n/2 + W \cos \alpha \right)$$

$$= \left( \frac{2\pi \rho_w H_s^{-2}}{T_s U^3} \right) \cdot \left( gT_s/4\pi + W \cos \alpha \right)$$

During the Endre Dyrøy experiments the only oceanographic parameter registered was the significant wave height. For simplicity we will here assume a theoretical relationship between wave period $T_s$ and wave height which follows from the Pierson-Moscowich spectrum. For this energy spectrum we have (Horjen and Vefsnmo, 1985):

$$T_s = K \sqrt{H_s/g} \quad K \approx 12.077$$

Using now also the second hypothesis the final form of the mean horizontal impact-generated spray flux at the level $z$ becomes

$$G = a \left( \rho_w g H_s/U^2 \right) \cdot \left( \frac{\sqrt{g H_s}}{4\pi} + W \cos \alpha \right) (2z/H_s - 1)^b$$

where the height distribution has been scaled by $H_s/2$.

$a$ and $b$ are constants to be determined from measured spray flux values. These constants will depend on type and what part of the ship we consider.

Results of the spray flux measurements on "Endre Dyrøy" are reported in Horjen et al. (1986). Four spray collectors were placed at the front mast (14 m from the bow) at elevations 1.10 m, 2.00 m, 3.60 m and 5.35 m above the base of the mast, which was 5.5 m above the water line. The highest wind speed was 18 m/s which means that the contribution from wind-generated spray may be neglected compared to the collision-generated part.
Values of \( a \) and \( b \) obtained by a least squares analysis are given in Table 3.1 below.

Table 3.1. Constants in Eq. 3.9 ( \( r \) = correlation coefficient)

<table>
<thead>
<tr>
<th>( \alpha^\circ )</th>
<th>( a )</th>
<th>( b )</th>
<th>( r )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>2.3489 ( \times 10^\circ )</td>
<td>-2.0907</td>
<td>0.876</td>
</tr>
<tr>
<td>15</td>
<td>6.2430 ( \times 10^\circ )</td>
<td>-4.2934</td>
<td>0.956</td>
</tr>
<tr>
<td>45</td>
<td>2.2979 ( \times 10^\circ )</td>
<td>-4.1966</td>
<td>0.868</td>
</tr>
</tbody>
</table>

Based on these results the following expressions are proposed for arbitrary values of the (corrected) heading:

\[
\begin{align*}
\alpha^\circ < 15^\circ \text{ or } \alpha^\circ > 345^\circ : a &= 2.35 \times 10^\circ, \\
15^\circ < \alpha^\circ < 345^\circ : a &= 6.87 \times 10^{-\circ} \left(1-0.941 \cos \alpha^\circ \right), \\
b &= -2.1
\end{align*}
\]

During spray impingement on a vertical plate the instantaneous spray flux normal to the icing collector is now given by

\[
R_m = \left( \frac{G}{N_{t_r}} \right) \sin \psi. \quad (3.10)
\]

The spray frequency \( N \) and the duration \( t_m \) of a single spray were not measured on "Endre Dyrøy" and the literature contains only some few reported measurements from other ships. From a physical point of view there should be some correlation between the spray frequency and the collision frequency of significant waves. According to Zakrzewski (1987) in the mean about every second significant wave produces spray on a MFV-vessel. We will adopt this assumption in our analysis which means that the spray frequency may be expressed by

\[
N = \frac{1}{2} \frac{W_r}{\lambda_s} \quad (\text{s}^{-1}) \quad (3.11)
\]

where \( W_r \) is the relative velocity between significant waves and the ship:

\[
W = gT_s/(2\pi) + W \cos \alpha \quad (3.12)
\]

Zakrzewski (personal communication) has measured the duration and median droplet diameter of single sprays impinging on the superstructure of MT "Zandberg", giving mean values of 2.9 s and 1.8 mm respectively. Since the size of "Endre Dyrøy" is not much different from this ship we shall in our analysis assume the same parameter values.

4. ICING TEST RESULTS.

In addition to the sea spray measurements ice thicknesses were recorded on seven elements placed on the front mast: two vertical
panels, two vertical railings and three vertical pipes. The dimensions of these elements are listed in Table 4.1. These measurements took necessarily place at colder weather situations than the sea spray measurements. Data exists for two icing periods, the first one lasted six hours on Mars 13, 1985 while the second lasted three hours on January 17, 1986. In both cases wind (and presumably the wave) direction and the course of the ship were the same, i.e. the heading was 0°. Observed and calculated environmental conditions used as input to the icing model are given in Table 4.2.

Table 4.1. List of icing test elements with maximum height \(Z_{\text{max}}\), minimum height \(Z_{\text{min}}\) and width or diameter (D).

<table>
<thead>
<tr>
<th>Element No</th>
<th>Type</th>
<th>(Z_{\text{max}}) (m)</th>
<th>(Z_{\text{min}}) (m)</th>
<th>D (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Panel</td>
<td>7.10</td>
<td>6.10</td>
<td>1.00</td>
</tr>
<tr>
<td>2</td>
<td>Panel</td>
<td>10.10</td>
<td>9.10</td>
<td>1.00</td>
</tr>
<tr>
<td>3</td>
<td>Railings</td>
<td>6.90</td>
<td>5.10</td>
<td>0.05</td>
</tr>
<tr>
<td>4</td>
<td>Railings</td>
<td>8.60</td>
<td>6.90</td>
<td>0.05</td>
</tr>
<tr>
<td>5</td>
<td>Pipe</td>
<td>8.60</td>
<td>7.60</td>
<td>0.05</td>
</tr>
<tr>
<td>6</td>
<td>Pipe</td>
<td>8.60</td>
<td>7.60</td>
<td>0.30</td>
</tr>
<tr>
<td>7</td>
<td>Pipe</td>
<td>8.60</td>
<td>7.60</td>
<td>0.50</td>
</tr>
</tbody>
</table>

Table 4.2. Observed and calculated input parameters to the icing model for two icing periods on "Endre Dyrøy".

| Period No. | Obs. No. | Observed parameters | Calculated param. | Ice thicknesses were recorded every three hours at the centre and at the top and bottom of each icing test element. Mean values of these observations and corresponding model mean values (calculated in the same way) are given in Table 4.3 which also contains calculated values of cumulative ice masses and "effective" freezing fraction \(n=\frac{M_r(T)}{M_i(T)}\). Model ice thickness profiles on the first four elements are shown in Figure 4.1.

For simplicity icing intensity on cylindrical elements were only calculated along the stagnation line. Total ice load was estimated assuming constant ice thickness on the front side in the wind direction.
Table 4.3. Observed and model mean ice thickness ($h_{obs}, h_{mod}$), model ice mass ($M_{mod}$) and "effective" freezing fraction ($n$) for the seven icing test elements at the front mast of "Endre Dyrøy".

<table>
<thead>
<tr>
<th>El. No</th>
<th>ICING PERIOD NO 1</th>
<th>ICING PERIOD NO 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Observation No 1</td>
<td>Observation No 2</td>
</tr>
<tr>
<td></td>
<td>$h_{obs}$</td>
<td>$h_{mod}$</td>
</tr>
<tr>
<td>1</td>
<td>6.9</td>
<td>5.3</td>
</tr>
<tr>
<td>2</td>
<td>2.6</td>
<td>1.9</td>
</tr>
<tr>
<td>3</td>
<td>2.7</td>
<td>7.8</td>
</tr>
<tr>
<td>4</td>
<td>6.5</td>
<td>3.4</td>
</tr>
<tr>
<td>5</td>
<td>3.0</td>
<td>2.9</td>
</tr>
<tr>
<td>6</td>
<td>4.7</td>
<td>2.9</td>
</tr>
<tr>
<td>7</td>
<td>4.5</td>
<td>2.9</td>
</tr>
</tbody>
</table>

Fig. 4.1. Model ice thickness profiles on four icing test elements of "Endre Dyrøy" after icing period No 1 (6 hours).
5. DISCUSSION

Observed and computed icing rates in mm/hr (mean values for the last 3 hours of registrations) are compared in Fig. 5.1. One of the observations gave negative icing rate and is omitted in this figure. The best least squares fit through the origin has a slope of 0.968 while the correlation coefficient is r = 0.688. Considering all the assumptions made in the model the results look rather promising. There are, however, several factors which may alter the results given by our model. We shall give a brief discussion of some of these factors below:

1. During the "Endre Dyrøy" icing experiments snow fall was observed in either case. Snow accretion mixed with sea spray was included in the stationary icing model of Horjen and Vefsnmo (1984). This model was applied for a rig icing case showing that the ice weight contribution due to snow could be significant.

2. Since spray frequency and duration of a single spray was not registered on board "Endre Dyrøy", the values used in the model may differ from the values specific for this ship. We have more confidence in the formula used for spray mass flux; however, spray production is a rather stochastic process giving large scatter in measured values for the same test condition.

3. In the model we have assumed no air inclusion in the accreted ice, i.e. minimum ice thicknesses have been calculated.

4. The value of \( \sigma \) used in the model is based on both wind tunnel and field data. The majority of these data give \( \sigma \)-values in the range from 0.2 to 0.5. If only the field tests are considered the mean value of \( \sigma \) becomes 0.44. It is likely that this parameter depends in some way or another on the test conditions.

Fig. 5.1. Comparison of calculated and measured rate of icing on the seven icing test elements of "Endre Dyrøy". Continuous line represents the best least squares fit through the origin.
6. CONCLUSIONS

Based on a limited amount of sea spray data from the observation vessel "Endre Dyrøy" we have shown that satisfactory prediction of ice accretion is possible using a new time-dependent icing model. The model does not consider the contribution of a possible snow fall which in some cases may increase the total ice load considerably. We therefore suggest that future research on marine icing modelling should concentrate on including the effects of snow mixing with the impinging sea spray.

REFERENCES


A system is described for the measurement of static and dynamic forces due to wind and ice-loads on a 322 m high guyed lattice TV-mast. Results from measurements during the winter 1988-1989 are presented.

1. INTRODUCTION

Atmospheric icing of structures in arctic areas can give serious problems. For example, TV-masts in northern Sweden and Finland can accrete ice loads of a magnitude of 4 to 13 kN per meter of the mast, Mikaelsson (1988), Lehtonen et al. (1986).

In order to get a better knowledge of the phenomenon a program of measurements has been started at the mast on the mountain Akkanälke close to Arvidsjaur in northern Sweden.

The mast was built in 1986. Its main dimensions are given in Fig. 1.

2. SYSTEM FOR MEASUREMENTS

The system is composed of five parts, see Fig. 2:

(A) Three modules for force measurements in the lower parts of the three upper guy ropes. Four foil strain gauges are glued to each guy rope connection in a full bridge. Signals are amplified in a insulated box, see Fig. 3.
One module for force measurements in the three legs on which the mast is standing. The module is built in the same way as the modules in (A).

Two modules for temperature and moisture measurements (Vasiala HMP 1258).

One module for wind direction and velocity.

A data acquisition system.

Figure 1. TV-mast in Arvidsjaur. Danielsson et al. (1989)
Figure 2. Outline of measurement system. Danielsson et al. (1989)
3. SOME RESULTS

Some results from March 1989 are given in Figures 4 and 5, Danielsson et al. (1989). It can be seen that oscillations often take place in guy rope 3 which is connected to the upper part of the southern leg C. Winds from the south are dominating during this period. On March 12 there are quite large oscillations in leg C. More detailed measurements from this period are shown in Figure 5.

From the measurements it will be possible to check design methods for static and dynamic loads, eigenfrequencies, drag coefficients for wind loads, risks for fatigue failures in bolts, and which weather conditions that give the most intensive ice growth and the most dangerous load cases.
Figure 4. Load on guy ropes and legs, March 6-12, 1989
Figure 5. Load on guy ropes and legs, March 12, 1989
ACKNOWLEDGEMENTS

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REFERENCES


PREDICTION OF VESSEL ICING: A 1989 UPDATE

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ABSTRACT

The NOAA vessel icing algorithm is evaluated against theoretical advances. The most difficult factor is influence of sea temperature. Modeling demonstrates the importance of supercooling of spray during its trajectory to extreme ice accretion. This occurs when sea temperatures are less than 2-3°C above the saltwater freezing point. The sea surface temperature term in the NOAA algorithm is consistent with the supercooling hypothesis and a further category of "extreme" icing is added, which can explain anecdotal cases greater than 5 cm h⁻¹. A wave height/wind speed threshold is 5 m s⁻¹ for a 15-m vessel, 10 m s⁻¹ for a 50-m large trawler and 15 m s⁻¹ for a 100-m vessel, developed from seakeeping theory. These wind speeds are exceeded 83%, 47% and 15% during February in the Bering Sea.

1. INTRODUCTION

Vessel icing, and subsequent loss of stability, is a hindrance for expanded marine operations in high latitudes. The rate of icing depends on wind speed, air temperature and sea temperature and the characteristics, speed and heading of the vessel. Because the dependence of icing on the three environmental parameters is not a simple linear combination, vessels often depend on weather services for warnings of potential icing (Zakrzewski et al., 1988a). We review the process of vessel icing with regard to sea temperature and vessel length.
2. THE PRESENT ALGORITHM

The NOAA ice accretion chart has been produced daily since winter 1986-87 (Feit, 1987). The chart is based on three categories of potential icing rate (Table 1) with predictor (see notation).

\[
PR = \frac{V_a (T_f - T_a)}{1 + 0.4(T_w - T_f)}
\]  

(1)

Table 1. Categorical forecast procedure (Overland, et al., 1986; OPPC).

<table>
<thead>
<tr>
<th>Icing Class</th>
<th>Light</th>
<th>Moderate</th>
<th>Heavy</th>
<th>Extreme (Proposed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Icing Rate (cm h&lt;sup&gt;−1&lt;/sup&gt;)</td>
<td>&lt;0.7</td>
<td>0.7-2.0</td>
<td>&gt;2.0</td>
<td>&gt;5.0</td>
</tr>
<tr>
<td>Predictor (PR) (°C s&lt;sup&gt;−1&lt;/sup&gt;)</td>
<td>&lt;20.6</td>
<td>20.6-45.2</td>
<td>&gt;45.2</td>
<td>&gt;70.0</td>
</tr>
</tbody>
</table>

Input fields are surface air temperature and wind speed from the National Meteorological Center (NMC) spectral forecast model and a blended satellite and ship sea-surface-temperature analysis. The coefficient between icing rate and the predictor value, and the coefficient of the sea temperature correction, 0.4°C<sup>−1</sup>, were determined from a set of 58 open-ocean observations in Alaskan waters taken when the vessels were not heading downwind (Pease and Comiskey, 1985). The functional form of (1) is roughly consistent with a heat balance

\[
(1 + \phi(T_w - T_f)) \frac{dH}{dt} - A V_a (T_f - T_a)
\]  

(2)

The right side of (2) represents heat transfer. The \(\phi\) term represents the cooling of the seawater which both remains accreted to the surface and runs off the ship. The cooling of the water which remains accreted is a small effect (Stallabrass, 1980), but the total water volume as represented by the inverse of the accretion fraction, F, can be large and explains the strong empirical dependence of icing rate on sea temperature (OPPC). The F ratio is used because it varies more slowly than either icing rate or water supply (Perry, 1963; Makkonen, 1988).
Notation

\[ V_a \] wind speed
\[ T_f \] freezing point of seawater
\[ T_w \] sea temperature
\[ T_a \] air temperature

\[ \frac{dH_i}{d\tau} \] icing rate
\[ -C_w L_i^{-1} F^{-1} \]
\[ A \] \( -C_H \rho_a C_a \rho_i^{-1} L_i^{-1} \)
\[ F \] accretion fraction, ice growth/water delivered
\[ \rho_a, \rho_i \] density of air and vessel icing
\[ C_w, C_a \] specific heat of seawater and dry air
\[ L_i \] latent heat of freezing for spongy sea ice
\[ C_H \] transfer coefficient for heat flux

\[ \omega_e, \omega \] frequency spectrum for pitch, heave and waves
\[ \bar{u} \] ship speed
\[ \gamma \] angle between heading and sea
\[ F_n \] Ship Froude number \( \bar{u}(gL)^{-\frac{1}{2}} \)
\[ g \] gravity
\[ L \] ship length
\[ m_o \] mean square of relative displacement
\[ m_2 \] mean square of relative vertical velocity
\[ h \] freeboard
\[ H_{1/3} \] significant wave height

Although OPPC emphasizes categorical forecasts for operational forecasts, there is concern that the algorithm quantitatively overpredicts icing rate. Based on the Pease and Comiskey data set potential icing rate was defined as the mean of the maximum reported rate and the event rate, the total amount accreted divided by event duration (Figure 1). The median icing rate for moderate icing is 1.7 cm h\(^{-1}\), the median event rate is 1.0 cm h\(^{-1}\). For heavy icing the median icing rate is 5.1 cm h\(^{-1}\), compared to a median event rate of 2.5 cm h\(^{-1}\). Of course there is even more variation from vessel to vessel. It is evident that the magnitudes for icing rate categories
depend on procedural definitions by at least a factor of 2-3. Our heavy icing threshold for potential icing of 2.0 cm h\(^{-1}\) is not inconsistent with a 0.7 cm h\(^{-1}\) definition (Zakrzewski et al., 1988a). For operational forecasts we recommended that icing categories, light, moderate, heavy, extreme, refer to ranges of meteorological conditions, not absolute icing rates.

![Figure 1. Comparison of the NOAA algorithm with icing data (Pease and Comiskey, 1985). Circles are maximum icing rate and crosses are event rate. Squares are the average of these rates.](image)

3. THE VESSEL ICING PROCESS AT LOW AND MODERATE SEA TEMPERATURES

A second concern of OPPC is (1) may overpredict at low sea temperatures because \( \cdot \) was fit to the Alaskan data set, with mean sea temperature of 3.6\( ^\circ \) (Pease and Comiskey, 1985), compared to the Stallabrass Atlantic data set of 0.7\( ^\circ \) (Roebber and Mitten, 1987). Modeling (Makkonen, 1987; Vefsnmo and Horjen, 1987; Zakrzewski and Lozowski, 1987; Zakrzewski et al., 1988b) suggests that at low sea temperatures (<0\( ^\circ \)) spray is cooled to supercritical values and becomes a heat sink, while large volume of warm sea spray continues as a heat source (Figure 2a and b). Supercooling combined with small accretion fractions give the strong sea-surface temperature dependence shown in Figure 2.

These studies support the functional form of the denominator in (1) at near-freezing sea temperatures. Lee (1958), De Angelis (1974) and George (1975) report icing rates in excess of several centimeters per hour near ice edges in the Barents Sea, Laborador Sea and Denmark Strait. A fourth icing category, extreme, is suggested for the NOAA
algorithm (Table 1) at PR > 70 m s⁻¹°C. The meteorological predictor will in general only obtain this value at near freezing sea temperatures (Figure 3a and 3b).

\[ U_{10} = 14 \text{ m s}^{-1} \quad \text{WIND SPEED} \quad U_{10} = 30 \text{ m s}^{-1} \]

Figure 2a and b. Ice growth rates for the top and bottom of a central column of the ship's superstructure as a function of spray delivery and sea surface temperature. There is a major dependence of icing rate with sea temperature (From Zakrzewski, et al., 1988b).

Figure 3a. Sea surface temperatures for 7–9 March 1988, Alaskan waters (Courtesy R. Scheidt). Cold sea temperature occur near the ice edge.

Figure 3b. Sea surface temperatures for 10–16 March 1970, Eastern Canada (Stallabrass, 1971). Note the large area of subzero temperatures north of Newfoundland.
4. ICING THRESHOLD VERSUS VESSEL SIZE

The NOAA algorithm is based on thermodynamic arguments and empirical data; it assumes an adequate supply of water reaches the deck. For small fishing vessels (20 m) the wind speed for moderate icing is sufficient to provide spray to forward deck areas. For large trawlers (50 m), coastal freighters (75-150 m) and military vessels there is a threshold wave height in addition to the necessary heat flux. Sawada (1966) reports a threshold wave height of 2.5 m for icing; this is equivalent to 10.0 m s$^{-1}$ wind for 200 km fetch. Zakrzewski (1987) reports a threshold wind velocity of 10 m s$^{-1}$ for 35-40 m Soviet MFV type vessels. We suggest a spray generation threshold as a function of length based on seakeeping theory. Note, however, that seakeeping depends on individual ship characteristics and vessel speed.

Linear response analysis is successful for heave and pitch of a vessel forced by an ocean wave spectrum (St. Denis and Pierson, 1953)

$$
\phi_{\theta\theta}(\omega) = |H_{\theta\zeta}(\omega)|^2 \phi_{\zeta\zeta}(\omega) \\
\phi_{zz}(\omega) = |H_{z\zeta}(\omega)|^2 \phi_{\zeta\zeta}(\omega)
$$

$H_{\theta\zeta}$ and $H_{z\zeta}$ are the response functions that relate pitch, $\theta$, and heave, $z$, spectra to the ocean wave spectrum $\phi_{\zeta\zeta}$. Encounter frequency, $\omega_e$, is

$$
\omega_e = \omega - \frac{\omega^2}{g} u \cos \gamma
$$

Spray generation is expected when pitch is large. With the assumption that a thin ship responds hydrostatically to waves and that wave spectra can be scaled by the significant wave height, the root-mean-square of pitch and heave has been determined as a function of non-dimensional ship speed, the vessel Froude number, $F_n = \bar{u}/\sqrt{gL}$ (Price and Bishop, 1974).

Deck wetness due to shipping water occurs when the relative displacement between the ship and sea surface exceeds local freeboard

$$
\varepsilon_b(t) = z(t) + 0.5L\theta(t) - \zeta(t)
$$

If the relative displacement of the bow is a narrow-banded process described by a Rayleigh probability function, the expected number of deck wettings per unit time is
For vessels steaming directly into waves, figure 4 gives the limits on non-dimensional forward speed to avoid more than 1 in 20 waves overtopping the deck as a function of significant wave height and freeboard (Price and Bishop, 1974). For example, a 100-m ship with a 7 m freeboard can expect wetting greater than 5% of the time when traveling greater than 9.5 m s\(^{-1}\) \((F_n = 0.3)\) in a sea of 6 m significant wave height. Figure 5 gives the number of wetness events per hour for a ship of freeboard/length ratio of 0.065. For all freeboards the onset of wetness occurs near a \(H_{1/3}/L\) ratio of 0.04. For larger freeboard/length ratios expected wetness is a strong function of forward speed.

\[
H^H = \frac{1}{2\pi} \left( \frac{m_0^2}{m} \right)^{1/4} \exp(-h^2/m_0)
\]

Figure 4. The limit on non-dimensional forward speed to avoid 1 in 20 wave overtoppings of the vessel as a function of freeboard and significant wave height.

Figure 5. Expected number of deck wettings per hour as a function of significant wave height and vessel speed. A 0.04 significant waveheight-length ratio is adopted for the beginning of significant spray delivery.

Spray onto decks and superstructures is probably fully developed at the 5% wetness criteria. For a 0.04 \(H_{1/3}/L\) ratio the wind speed threshold for icing as a function of vessel length is Table 2. The bottom row indicates for winter Bering Sea that the likelihood of encountering icing conditions is small only for vessels greater than 150 m.

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Table 2. Relation of vessel length to minimum wind speed for ship icing.

<table>
<thead>
<tr>
<th>Vessel length (m)</th>
<th>15</th>
<th>30</th>
<th>50</th>
<th>75</th>
<th>100</th>
<th>150</th>
</tr>
</thead>
<tbody>
<tr>
<td>Significant wave height (m)</td>
<td>0.6</td>
<td>1.2</td>
<td>2.</td>
<td>3.</td>
<td>4.</td>
<td>6.</td>
</tr>
<tr>
<td>Wind speed (m/s) at 200 km fetch</td>
<td>5.0</td>
<td>7.4</td>
<td>9.8</td>
<td>12.5</td>
<td>15.</td>
<td>20.</td>
</tr>
<tr>
<td>Percent of observations with this wind speed or greater for Bering Sea in February (Brower et al., 1977)</td>
<td>83</td>
<td>69</td>
<td>47</td>
<td>27</td>
<td>15</td>
<td>4</td>
</tr>
</tbody>
</table>

Figure 6. Vessel length versus potential icing rate for the Pease and Comiskey (1985) data set. Vessels of 50 m showed icing during moderate meteorological conditions.

Figure 6 plots observed wind speed versus vessel length from the Alaskan data set. No cases were obtained with a wind speed less than 8 m s⁻¹. There is a wind speed threshold for vessels greater than 60 m.

5. RECOMMENDATIONS

Forecasts of vessel icing are primarily dependent on the accuracy of meteorological forecasts of cold air advection. Extremely hazardous regions with sea temperatures less than 1-2°C occur near ice edges in northern seas; but the extent of these regions is small compared to regions of 1-6°C (Figure 3).
There is little reason for poor 24-36 hour forecasts of vessel icing conditions, and outlooks to 72 hours. At high latitudes the geostrophic adjustment of spectral atmospheric models is theoretically superior to grid point models in predicting changes in dominant air masses. Increased vertical resolution has helped forecasts of air temperature. Numerical guidance must be supported by experienced marine forecasters who recognize a cold air advection icing event from all data sources. Vessel operations have the responsibility on interpretation of forecasts for their vessel's situation.

6. ACKNOWLEDGMENTS

This paper is a contribution to the Marine Services Project at PMEL. We have enjoyed discussions with D. Feit, R. Scheidt, and P. Zakrzewski. Contribution No. 1057 from NOAA's Pacific Marine Environmental Laboratory.

7. REFERENCES

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A STRAIGHTFORWARD METHOD FOR CALCULATION OF

ICE RESISTANCE OF SHIPS

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Arctic Sea Transportation

ABSTRACT

This paper presents an engineering tool for the evaluation of ice resistance. The main parameters that influence ice resistance are already known. This paper is an attempt to transform this knowledge into a useful calculation formula.

The parameters included in the method are: main dimensions, hull form, ice thickness, friction and ice strength.

First, the paper presents the parameters and their importance. Then straightforward formulas are developed, in which the influence of each factor is generated using dependences that approximate the physical processes of icebreaking. Finally, the results are evaluated against full scale tests with different ships.

1. INTRODUCTION

Ice resistance can be estimated using experience from ships in service, model-scale testing or analytic formulas. Each method has its strong and weak points. The use of experience is reliable if the new design is close to some tested designs. This is not always the case today when new innovative solutions are being sought.

Model-scale testing has become reasonably reliable with the improvement of the model ice and testing techniques. The main drawbacks are the relatively high costs, and the slowness of the testing process.

Analytical methods are so far inexpensive, but are not reliable. Greater reliability will be achieved as the knowledge of the physics of icebreaking advances.
2. METHOD

The approach used in this paper is to identify the main components of the ice resistance and approximate their contribution with simple but physically sound formulas. In this method the whole icebreaking process is simplified, the goal being not to describe icebreaking with scientific exactitude but to create a tool for evaluation of ice resistance.

The aim is thus to achieve an uncomplicated method of estimating the resistance level and also of showing how resistance is affected by the main dimensions, the hull form and the friction. This method can never be a substitute for model testing; it is rather a tool for deciding what hull forms should be tested.

The main resistance components used are breaking, submersion and speed dependence. These are generally accepted as the main components of resistance and thus acceptable, although the truth can be more complicated. The underwater form of the icebreaker is approximated with flat surfaces, to make the calculations shorter.

3. BREAKING

The earliest attempts to calculate the ice resistance ignored the submersion component. When this component was found, it was overestimated and the breaking component underestimated.

One reason for the underestimation of the breaking process was that only the energy dispersed in bending the ice was considered. This part of the breaking resistance is small, as natural ice is quite rigid and is not greatly deflected prior to breaking.

A probable explanation of the high breaking resistance is that much energy is absorbed by the crushing of the ice prior to the final failure by bending.
In the present method the breaking process is simplified, all forces in the breaking process are generated by crushing the edges of the floes. In order to keep the calculations short, both deflection of the ice and trimming of the vessel are ignored. This simplification can cause underestimation of the breaking resistance in very thick ice, in which the vessel trims considerably.

3.1 CRUSHING AT THE STEM

Crushing at the stem in a wedge-shaped icebreaker is almost continuous. It seems that the force never grows great enough to break the ice in the bending mode. This is probably due to two reasons. One is that the bending failure force is greater at the stem than further aft, due to the different geometry. The other reason is that the ice is undamaged at the stem, whereas further aft there are clearly many microcracks due to the interaction at the stem.

The exact magnitude of the force is not known. It can be measured by instrumentating the stem, or perhaps by simultaneous recording of the breaking pattern and the trim of the vessel. As this has not yet been done, we have to estimate this force by making an intelligent guess. The average vertical force acting on the ice is estimated as:

\[ F_v = 0.5 \sigma \alpha H_{ice}^2 \]  

(1)

In this formula, \( \sigma \) is the bending strength of the ice, and \( H_{ice} \) is the ice thickness. Analysis of the force components using cumulative friction and assuming that the friction force acts along the verticals shows that the resistance force is:

\[ R_c = F_v \tan \phi + \mu \cos \phi + \sin \phi \] \((1 - \mu \sin \phi \cos \phi) \)  

(2)

![Figure 2. Stem crushing and vertical force.](image)
μ is the friction coefficient, phi (φ) is the stem angle, alfa (α) is the waterline entrance angle and psi is the angle between the normal of the surface and a vertical vector (ψ=αln(tanφ/sinα)).

This resistance term explains the great resistance experienced by small icebreakers. The ice resistance of an extremely narrow icebreaker is thus not zero.

The spoon-shaped or cylindrical bow is intended to eliminate this resistance term by changing the geometry at the stem. With a square bow a crushing zone can be seen at the edges and this resistance term is thus not eliminated /4/.

3.2 BREAKING BY BENDING

Ice is clearly broken in the bending mode some distance aft of the stem. Although the final failure is in the bending mode, this is preceded by crushing and shearing /7/. As the ship comes into contact with the sharp edge of the ice, the edge is crushed until the force is big enough to shear away a small piece of ice. The plane of failure is close to the contact area and the crushing continues in a similar way; the only change is that the breadth of the contact area increases. This process continues until the force transmitted through the contact area is big enough to cause a bending failure.

Figure 3 shows the geometry and force. The mathematical calculation of this process is shown in appendix 1. The result of the calculation is:

\[ R = k \cdot b \cdot (H_{ae}^2/l_c^2) \cdot \frac{(\tan \psi + \sin \phi \sin \alpha \cos \psi)}{(\sin \alpha \cos \psi)} \cdot (1 + 1/\cos \psi) \]  (3)

where the angles are defined in figure 1,k is a constant, H_{ae} is the ice thickness, l_c is the characteristic length of the ice and B is the breadth of the vessel. The characteristic length, which determines the size of the floes, is proportional to the thickness to the power of 0.75. Using the constants shown in appendix 1, the formula can thus be rewritten:

![Figure 3. Breaking by bending.](image-url)
This is an interesting approximation, for two reasons. One is that the resistance is proportional to the ice thickness to the power of 1.5. This is a very realistic value. The other point of interest is that the resistance is highly dependent on the breaking angle \( \psi \). This dependence has been observed earlier in full-scale tests /3/. These two points explain why conventional wedge-shaped bows are relatively inefficient in very thick ice.

4. **Submersion**

Model tests and underwater observations from full-scale tests have shown that when the ship is running in level ice the hull is almost completely covered by ice. In view of this observation, the calculation of the submersion component is uncomplicated. As ice is lighter than water, it is lifted against the hull and the resistance comes directly through the normal force and indirectly through the friction.

In calculating the friction component the bow is assumed to be completely covered by ice and the bottom to be covered for 70% of the length of the ship. This is because the stern region is not completely covered by ice. The ice is assumed to move along the verticals. The influence of ploughs is not taken into account. On the one hand, the plough reduces the area covered by ice, but on the other hand some energy is used to transfer the ice to the sides.

The resistance coming from the normal force is not calculated separately for all surfaces. Instead, this component is calculated through the potential energy. In this approach, it is only necessary to know the distribution of ice at the deepest section to calculate this term. The mathematical calculations are in appendix 2 and the result is:

\[
R_i = \delta \rho g H_{\text{ic}} (T^*(B+T)/(B+2T)) + \mu^*(A_u + \cos\theta \cos\phi \cos\psi A_j) \]  
(5)

where \( \delta \rho \) is the density difference between the water and the ice, \( g \) is the gravitational constant, \( H_{\text{ic}} \) is the ice thickness, \( L, B \), and \( T \) are the length, breadth and draft of the ship, \( \mu \) is the friction coefficient, \( A_u \) is the area of the flat bottom and \( A_j \) is the area of the bow. According to the formula the resistance is the loss of potential energy plus frictional forces. Using approximations for the area of the surfaces, we obtain the formula:

\[
R_i = \delta \rho g H_{\text{ic}} B^*(T^*(B+T)/(B+2T)) + \mu^*(0.7L - T/\tan\phi - B/(4\tan\alpha) + T^* \cos\phi \cos\psi \sqrt{(1/\sin\phi^2 + 1/\tan\alpha^2)}) \]  
(6)
For a frictionless hull, this resistance term is proportional to ice thickness times breadth times draft. For normal friction values, the importance of the draft is reduced and the length of the ship influences the result.

It is difficult to determine the true friction between the ship and the ice. Recent research has shown that it depends upon pressure and temperature. A reasonable approximation is 0.1 for a ship with low friction paint and close to 0.16 for a ship with normal antifouling paint. Another unresolved question is what allowance should be made for the snow thickness in the calculations. In the present method the pure ice thickness is used in the breaking calculations and ice plus snow thickness in the submersion calculations.

5. SPEED

Both the breaking and the submersion component are fairly well known. Their relative importance can be discussed and the accuracy of the formulas can still be improved, but these are minor questions.

The speed dependent component is more uncertain. It is important, as at normal operating speeds it accounts for about half of the total resistance. The exact reasons for this component are unknown, though many factors can be suggested. Such factors are: increase of breaking resistance, increase of submersion resistance, acceleration of ice floes, ventilation of ice floes and viscous drag.

The breaking resistance can increase if floe size decreased with increasing speed. The water pressure at the bow area is increased and can affect the forces needed to break the ice.

The speed will clearly influence the flow lines of the broken ice and the submersion component will therefore change with the speed. The friction component can also increase when the dynamic water pressure outside the ice increases or because the friction coefficient changes.

Acceleration of ice floes and the water close to the floes contribute to the resistance, but how much?

Full ventilation of the ice floes means that only air exists between the floes and the hull. The water pressure then creates a great normal force on the ice floes and thereby increases resistance due to the friction. This is obvious, but calculation of the ventilated areas is difficult and requires more research.

A viscous drag is created if there is only a very thin water film between the ice and the hull. The thickness of the water film is so far unknown, so it is hard to calculate this component.

At present we do not know how much each factor influences the resistance.
More research is clearly needed in this area before progress is possible. As the factors are not well known, it is futile to calculate this term at this stage. It seems possible that both the submersion and the breaking component are increased, and this assumption is used. Instead of calculating the increase of this term, the static components are used and the increase is approximated using empirical constants.

The resistance seems to increase fairly linearly with the speed. To obtain a dimensionless term, the increase in the breaking resistance can be assumed to be proportional to speed divided by the square root of ice thickness times the gravitational constant. In the same way the increase in the submersion term is proportional to speed divided by the square root of the length of the ship times g. Using two empirical constants we obtain the total ice resistance:

\[ R_{\text{total}} = (R_t + R_b)\left(1 + 1.4\frac{u}{\sqrt{gH_{\text{ice}}}}\right) + R_b\left(1 + 9.4\frac{u}{\sqrt{gL}}\right) \]

6. EXAMPLES

To test the formula it has been run against the results obtained with seven different ice-going ships in Baltic conditions. The Baltic was chosen to eliminate large differences in ice conditions and because a relatively large number of tests have been made in these conditions.

To check whether the formula accounts adequately for the size of the ship, it has been tested against three icebreakers with different displacements. The smallest is the harbour tug Jelppari, with a displacement of about 70 tons. The medium-size icebreaker is the relatively new Baltic icebreaker Otso, with a displacement of 8,000 tons. The largest icebreaker is the Arctic icebreaker Vladivostok, with a displacement of about 13,000 tons. The main dimensions and shapes of the ships are given in table 1 and the resistance in figure 4.

![Figure 4. Calculated resistance (line) and measured (dots).](image-url)
The formula seems to be fairly reliable for larger ships; for smaller ships, the speed dependent part is unreliable, although the calculated resistance is of the right order of magnitude.

To check how the formula can predict ice resistance for different hull shapes, it has been run against four rather small ships tested in about 0.5 metre ice. Two have rather poor icebreaking lines, as the bows are very sharp, their average breaking angle psi being 65 degrees. These are the 600 ton displacement Coast Guard cutters Valpas and Silma. At the time of testing, Valpas was four years old and had a coating of normal paint, Silma was eleven years old, but had low friction paint. The friction coefficient was not measured, but it should be between 0.1 and 0.16.

The ships with good breaking angles are Mergus (average psi = 22 degrees) and the Warc testing bow (average psi = 20 degrees). Mergus is of the same size as Valpas and is a small ferry operating in the sheltered waters of the archipelago outside Turku. Low resistance lines were easily achieved, as the ferry needed a large deck area, but not a large displacement.

The Warc bow is a 300 ton icebreaking bow, which was connected to a tug and was tested extensively in 1985. It is cylindrical and has a very small stem angle. The bow and test results are presented in more detail in ref /3/.

The formula predicts the ice resistance for some known ships with fairly good accuracy. This does not of course prove that the formula is "right" in all cases. The formula is rather a tool that can be used or abused. The greatest uncertainty attaches to its ability to predict how changes in the mechanical properties of the ice affect the resistance, as all the tests presented here have been made in almost identical ice conditions. Its reliability is better when the main dimensions of the ship change or if the shape of the ship changes.

Figure 5. Results with different bows (calculated = line, measured = dots).
An interesting question for both designers and ship owners is how much the ice resistance can be reduced by optimizing the lines. To evaluate this point the ice resistance was calculated for a medium-size icebreaker with two different bow forms. One was a conventional wedge-shaped bow, similar to that of Vladivostok, and the other a development of the cylindrical bow, called the conical bow. In the conical bow, the breaking angles are minimized at the shoulders as well to achieve minimal breaking resistance and good manoeuvrability.

According to the calculations, the resistance of the conical bow is about 40% less than that of the conventional bow. This means that the same ice can be broken with less than half the power, a significant improvement.

This improvement is of the same order as that reported with the Waas bow. The resistance of the Waas bow cannot however, be calculated with the present formula, as the breaking mechanism is different, at least at the sharp shoulders.

7. CONCLUSIONS

This paper has presented an easy method of calculating the ice resistance encountered by ice-going ships. The static resistance components are approximations of physical phenomena. The formulas have deliberately been kept short, as they are intended to be a tool in the design process and not a scientific explanation of the icebreaking process.

The speed dependency of this formula is too simple and requires refinement. This part of the formula should therefore be used with caution.

The formula shows that a significant improvement in icebreaking capability is possible with new hull shapes. This has been known earlier, but a relatively reliable method of estimating the resistance makes optimization for a certain operational profile much easier.

This method differs from earlier attempts to estimate the resistance with short formulas, as it takes account of both the friction and the shape of the ship. As space is restricted, it has not been possible in this paper to make any comparison with earlier methods.
APPENDIX 1. CALCULATION OF THE BENDING RESISTANCE

The edge of the cusp shown in figure 6 is crushed and sheared until the vertical force is great enough to break the ice in the bending mode.

The required vertical force is assumed to be:

\[ F_v = 0.5 \sigma_c \frac{H_{ic}}{} \]  \hspace{1cm} (8)

If the force is increases linearly as shown in figure 3, the average vertical force \( F_{ave} \) is:

\[ F_{ave} = 0.5 \frac{F_v}{F_v} \alpha l \]  \hspace{1cm} (9)

where \( \alpha \) is the vertical distance crushed and sheared and \( l \) is the length of the cusp. To determine \( \alpha \), we have to look closer at the crushing area and shearing forces. Using the two dimensional approach shown in figure 6 and classical stress analysis, we can calculate that the height of the crushing zone \( h_c \) is limited in the following way:

\[ h_c \sigma_c \leq 4 \frac{H_{ic}}{} \frac{\tau}{(3(1+\cos\psi))} \]  \hspace{1cm} (10)

where \( \sigma_c \) is the effective crushing strength and \( \tau \) is the shearing strength. The width of the crushing zone \( b \) is twice the penetration distance \( \alpha \) in the described geometry. Using this, we obtain a new expression for the vertical force:

\[ F_v = 2 \sigma_c \frac{h_c}{2} \alpha \cos\psi \]  \hspace{1cm} (11)

Using equations 8,10 and 11, we can rewrite equation 9 to obtain a final expression for the average vertical force associated with the breaking of one cusp:

\[ F_{ave} = (3/64) \sigma_c \frac{(\sigma_c / \tau) (H_{ic}^2)}{l} (1 + 1/\cos\psi) \]  \hspace{1cm} (12)
The total average vertical breaking force for the whole breadth (B) of the ship is the average vertical force for one cusp times the average number of cusps n, which according to a geometrical analysis is:

\[ n = B / (l^* \sin \alpha) \]  

(13)

where alpha is the angle between the water-line and the direction of the ship's motion.

Assuming that the ice is moving along the buttock lines, we obtain the resistance force \( R_x \) from the vertical force with the following formula:

\[ R_x = F_{ave} \cdot n \cdot (\tan \psi \cdot \sin \alpha + \mu \cdot \cos \phi / \cos \psi) \]  

(14)

Using equation 12, we finally obtain the bending resistance:

\[ R_x = (3/64) \sigma_s \cdot (\sigma_s / \tau) \cdot B^2 \cdot (H_{ice}^2 / l^2) \cdot (\tan \psi + \mu \cdot \cos \phi / (\cos \psi \cdot \sin \alpha)) \cdot (1 + 1 / \cos \psi) \]  

(15)

The length of the cusps \( l \) is proportional to the characteristic length of the ice \( l_c \), which is:

\[ l_c = (E \cdot H_{ice}^2 / (12 \cdot (1 - \nu^2) \cdot \rho_w \cdot g))^{0.25} \]  

(16)

where \( E \) is Young's modulus, \( \nu \) is the poisson coefficient, \( \rho_w \) is the density of the water and \( g \) is the gravitational constant.

Assuming that the length of the cusps is one third of this characteristic length and the shearing strength is equal to the bending strength, we obtain the following breaking resistance:

\[ R_x = (27/64) \sigma_s \cdot B^2 \cdot \frac{H_{ice}^2 \cdot \tau \cdot \rho_w}{(E \cdot (1 - \nu^2) \cdot \rho_w \cdot g)}^{0.25} \cdot (\tan \psi + \mu \cdot \cos \phi / (\cos \psi \cdot \sin \alpha)) \cdot (1 + 1 / \cos \psi) \]  

(17)

Using an elastic modulus of 2*10^9 N/m^2 and a poisson coefficient of 0.3, we obtain formula 4.

To make the calculations faster, average angles are used in the resistance computations. The average psi angle is, for example:

\[ \psi_{ave} = (2 / B) \int_{(0)}^{(B/2)} \psi(y) \, dy \]  

(18)
APPENDIX 2. CALCULATION OF THE SUBMERSION RESISTANCE

The submersion resistance is calculated separately for the loss of potential energy and the frictional resistance.

To calculate the loss of potential energy, we only have to look at the ice distribution at the deepest point of the ship which is generally the midship section. If the ice is assumed to be evenly distributed along the section, the ice cover has an effective thickness $H_\ast$, which is:

$$H_\ast = H_{ic} \cdot B / (B + 2T) \quad (19)$$

where $B$ is the breadth of the ship and $T$ is the draft. The potential energy lost is the lifting force times submersion draft. The submersion draft for the floes under the ship bottom is equal to the ship draft, and the average submersion draft for the side pieces is half the ship draft. The potential energy lost is therefore:

$$E_p = \delta p \cdot g \cdot H_\ast \cdot (B \cdot T + T \cdot T) \cdot \delta x \quad (20)$$

where $\delta p$ is the density difference between the water and the ice, $g$ is the gravitational constant and $\delta x$ is a small distance in the length direction. As force times distance is energy, we can conclude that the resistance due to the loss of potential energy is:

$$R_p = \delta p \cdot g \cdot H_{ic} \cdot B \cdot T \cdot (B + T) / (B + 2T) \quad (21)$$

The frictional resistance caused by the floes under the bottom is the lifting force times the frictional coefficient:

$$R_\varphi = \mu \cdot \delta p \cdot g \cdot H_{ic} \cdot A_u \quad (22)$$

where $A_u$ is the area of the flat bottom covered with ice. If the bottom is assumed to be completely covered with ice up to 70% of the length, the area in the simplified hull geometry is:

$$A_u = B \cdot (0.7 \cdot L - T \cdot \tan \phi - 0.25 \cdot B \cdot \tan \alpha) \quad (23)$$

For the bow region with ice moving along the verticals, the resistance due to frictional forces is:

$$R_\varphi = \mu \cdot \delta p \cdot H_{ic} \cdot A_\varphi \cdot \cos \psi \cdot \cos \phi \quad (24)$$
In this case the resistance force is reduced as the frictional force is
directed slightly downwards and as the bow plane is inclined and the normal
force therefore reduced. The total area of the bow planes is:

\[ A_f = B^*T^*\sqrt{(1/\sin \phi^2 + 1/\tan \alpha^2)} \]  \(25\)

The total submersion resistance is the resistance due to the loss of
potentional energy plus the resistance due to the friction. This total
submersion resistance is:

\[
R_s = 6\rho g H_{ntw} B^* (T^* (B + T)/(B + 2*T) + \mu^* (0.7*L - T/\tan \phi)
- 0.25*B/\tan \alpha + T* \cos \psi * \cos \phi * \sqrt{(1/\sin \phi^2 + 1/\tan \alpha^2)})
\]  \(26\)

### TABLE 1. MAIN PARAMETERS AND CALCULATED RESISTANCE AT 0 AND 2 m/s.

<table>
<thead>
<tr>
<th>SHIP</th>
<th>Jelppari</th>
<th>Otso</th>
<th>Vladiv.</th>
<th>Silma</th>
<th>Valpas</th>
<th>Mergus</th>
<th>Warc</th>
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<tr>
<td>L(wl)/m</td>
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<td>90</td>
<td>112</td>
<td>45</td>
<td>44</td>
<td>44</td>
<td>48</td>
</tr>
<tr>
<td>B(wl)/m</td>
<td>5.1</td>
<td>23.4</td>
<td>23.5</td>
<td>8.0</td>
<td>8.2</td>
<td>8.3</td>
<td>11.1</td>
</tr>
<tr>
<td>T/m</td>
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<td>7.4</td>
<td>9.5</td>
<td>3.8</td>
<td>3.7</td>
<td>3.3</td>
<td>3.3</td>
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<td>(\phi_{stem})</td>
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<td>26</td>
<td>32</td>
<td>32</td>
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<td>15</td>
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<tr>
<td>(\alpha_{stem})</td>
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<td>24</td>
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<td>16</td>
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<td>90</td>
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<tr>
<td>(\phi_{au})</td>
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<td>24</td>
<td>28</td>
<td>28</td>
<td>15</td>
<td>15</td>
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<tr>
<td>(\alpha_{au})</td>
<td>25</td>
<td>25</td>
<td>18</td>
<td>13</td>
<td>14</td>
<td>50</td>
<td>59</td>
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<tr>
<td>(\mu)</td>
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<td>0.36</td>
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<td>0.02</td>
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<td>31</td>
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<td>R(2)/kN</td>
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</tr>
<tr>
<td>R(2)/kN</td>
<td>59.8</td>
<td>570</td>
<td>590</td>
<td>254</td>
<td>254</td>
<td>254</td>
<td>254</td>
</tr>
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</table>
REFERENCES


ABOUT PHYSICAL MODELLING OF KINETIC FRICTION BETWEEN ICE AND SHIP

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ABSTRACT

In order to improve the physical modelling of kinetic friction between ice and ship, comparative series of friction measurements, both in the field and in the laboratory, have been made. The field measurements in full scale were made in authentic icebreaking conditions with special friction measuring devices known as friction panels and installed flush to the shell plating of two different ships. The corresponding model-scale measurements on scales of 1:10 and 1:20 were performed in the ice model basin at the Wärtsilä Arctic Research Centre. Laboratory measurements using a special friction test rig were also performed to study the influence of various parameters on ice friction.

The main target of the measurement series was to determine the model friction coefficient to be used in ice model tests. The measurements gave strong indications that the best full-scale/model-scale correlation in friction modelling is achieved with a model friction coefficient of 0.035-0.05, measured according to the recommendations of the ITTC Ice Committee.

The influence of snow, water, surface roughness of the shell plating, speed and normal force on ice friction was found to be so essential that in friction modelling these parameters have to be taken into account precisely. For many parameters this can be done by defining the test conditions precisely, but the normal force dependence of the friction coefficient results in scale dependence in friction modelling.

1 GENERAL

The mechanical friction between ice and ship has a great influence on the ice performance of an icebreaking ship. In some cases, more than 50 percent of the ice resistance of an ice-going ship may be due to this friction /1/. Also, the role of the friction is equally important in model scale. In model scale, however, the friction between model ice and model is not a question
of performance; the surface and the friction coefficient of the model have to be sufficient to simulate full-scale friction phenomena in model scale as accurately as possible.

In light of the above, it is easy to understand the importance of correct model friction to the reliability of ice model testing as a whole. But in spite of this importance and the apparent simplicity of the commonly used friction scaling law, the model should have the same friction coefficient as the ship, the friction is not adequately modelled to date. There have been two basic reasons for this inadequate friction modelling. First, the friction phenomena in full scale in the authentic ice breaking conditions have been inadequately known, and second, the model coating technology in model scale has been insufficient. The 'correct' friction coefficient of the model has therefore been determined by comparing the measured full- and model-scale values of quantities affected by the friction, such as the ice resistance of a ship. In addition, it has been necessary to use empirical friction correction factors for full-scale predictions based on model tests. It is most likely that such friction modelling does not lead to the correct model friction coefficient from the point of view of the friction, although it does produce the model friction coefficient needed to compensate for all the possible errors made in model testing, in full-scale prediction procedures and in full-scale testing.

When a new model coating method, the so called Intermix-method /6/,/10/, was developed at Wärtsilä Arctic Research Centre (WARC) in the first half of the '80's, a better chance for more accurate friction modelling was achieved. Together with the new model coating method these friction measurements are an attempt to elevate friction modelling to a new, higher level, where the friction is modelled as purely as possible from the point of view of the friction. This is done by measuring and studying the friction itself by separating it from the other quantities normally measured in full- and model-scale ice tests. This basic idea in modelling the friction separately from other quantities should also make the results of this study, carried out mostly with ships, applicable to ice model testing of off-shore structures.

This study deals only with the kinetic friction, so that the friction coefficient in this paper is the kinetic friction coefficient.

2 MEASUREMENTS

The following six series of measurements were carried out in both the field and in the laboratory.

2.1 Full-scale friction panel measurements on the MS Protector with the WARC testing bow

The friction between ice and the hull of the icebreaker bow was measured in authentic icebreaking conditions during the full-scale trials of the MS Protector with the WARC testing bow /2/,/7/. The measurements were made
by means of two special friction measuring devices or 'friction panels', installed flush to the shell plating of the bow. The smaller or high pressure panel was 260 mm in diameter, and it was located just below the waterline of the bow, so that the edge of the unbroken ice field hit the panel and at least the upper edge of the ice was crushed against it. The bigger or 'low pressure' panel was 1000 mm in diameter, and it was located lower in the flat bottom area of the bow, so that broken and submerged iceblocks slid over its surface. Both panels were coated with Inerta 160. To measure the forces acting on the panel the measuring plates were connected to the hull of the bow through six and seven force transducers in the smaller and larger panel, respectively. The MS Protector with the WARC testing bow and the locations and the construction of the panels are shown in figure 1.

The MS Protector with the WARC testing bow, locations of the friction panels, and the construction of a panel.

The measurements with the panels in the WARC testing bow were carried out in the winter of 1985 in the Gulf of Finland under the following ice conditions:
- in level ice, 0.30 to 0.90 m thick, with and without snowcover
- in ridges
- in channels

2.2 Full-scale friction panel measurements with the IB Otso

Three friction panels similar to the ones in the WARC testing bow were also installed in the hull of the IB Otso in the locations shown in figure 2.
**IB OTSO, MAIN DIMENSIONS:**

LENGTH at CWL 90.00 m  
BEAM at CWL 23.35 m  
DRAUGHT at CWL 7.30 m  
SHAFT POWER 15.00 MW  
OPEN WATER SPEED 18.50 kn

![Ship Diagram]

Fig. 2: The locations of the friction panels in the IB Otso.

The two upper panels, the so called shoulder and bow panels, were 300 mm in diameter and they were installed into the ice zone of the hull. These panels were coated with stainless steel. The third or 'low pressure panel', was 700 mm in diameter, and it was installed lower in the hull. The low pressure panel was coated with Inerita 160.

The friction panel measurements with the IB Otso were carried out in the winters of 1986 and 1987 in the Bay of Bothnia under the following ice conditions:
- in level ice 0.80 m thick with snowcover
- in ridges

2.3 Friction test rig measurements in the laboratory /5/

To study the influence of some parameters on the friction a special friction test rig, shown in the schematic plan in figure 3, was constructed.

![Friction Test Rig Diagram]

Fig. 3: The schematic plan of the friction test rig.
The measurements with this test rig were carried out at WARC during the
winter of 1987. Natural ice from the Gulf of Finland outside Helsinki was
used in the tests, which were performed with ice with and without snowcover,
in dry conditions and under water. Test plates with different coatings were
including: Inerta 160, smooth steel, rough steel, slightly corroded steel
and heavily corroded steel.

2.4 Model-scale friction panel measurements with the 1:10 model of the
MS Protector and the WARC testing bow

The friction panel measurements corresponding to the ones performed in full
scale with the WARC testing bow were also performed in model scale /7/. The
friction panels, the dimensions of the measuring plates of which were scaled
down according to the scaling laws, were installed in the 1:10 model of the
MS Protector with the WARC testing bow in locations corresponding to those
in full scale. Because of the small size of the model-scale panels they had
to be constructed in a different way from the full-scale panels, although the
same quantities as in full scale were of course also measured in model scale.
A schematic plan of a model-scale friction panel is shown in figure 4.

![Fig. 4: The construction of a model-scale friction panel.](image)

The model-scale tests were carried out with two different friction coefficients
of the model, namely 0.013 and 0.097, measured according to the recommendations
of the International Towing Tank Conference, the Performance in Ice-Covered
Waters Committee (ITTC, Ice Committee) /10/. These friction coefficients
were achieved using the Intermix-method /6/,/10/, which is the standard model
coating method at WARC.

The model tests were performed in level ice 60 mm thick ,and 55 kPa in
flexural strength, corresponding to 0.60 m and 550 kPa in full scale. This
represents the ice conditions encountered during full-scale measurements.

The model ice used in this as well as in all of the model test series was
WARC FG-model ice /2/.
2.5 Model-scale friction panel measurements with the 1:20 model of the IB Otso

The model-scale measurements corresponding to those performed in full scale with the IB Otso were also carried out at WARC. Three scaled friction panels were installed in the 1:20 model of the IB Otso at locations corresponding to those in full scale. The tests with the model of the IB Otso were also performed with two different model friction coefficients, namely 0.061 and 0.151 (ITTC).

The model tests of the IB Otso were performed in level ice 40 mm thick and 24 kPa in flexural strength, corresponding to 0.80 m and 480 kPa in full scale and representing the ice conditions encountered during full-scale measurements.

2.6 Friction measurements with segmented model in two dimensions

Ice model tests with a simplified, segmented model in two dimensions have been performed at WARC. The model, which is shown in schematic plan in figure 5, was built of five different segments, some of which were instrumented so that the friction between the ice and the segments could be measured.

![Fig. 5: The segmented 2D-model.](image)

The tests with the 2D-model were only performed with one model friction coefficient, namely 0.060 (ITTC). The ice condition in the tests was level ice, and tests were run in two different ice thicknesses of 30 and 50 mm. The flexural strength of the ice in both thicknesses was 20 kPa.

2.7 Friction measurements according to the recommendations of the ITTC Ice Committee

In all of the ice model test series the friction coefficient of the model was measured according to the recommendations of the ITTC Ice Committee. The results of some of the measurements are also presented.
3 RESULTS

3.1 Mean values of the friction coefficients measured for the full-scale friction panels

The mean values of the friction coefficients measured in different ice conditions for the full-scale friction panels in both the WARC testing bow at front of the MS Protector and in the IB Otso are presented in Table 1.

Table 1: The mean values of the friction coefficients measured for the full-scale friction panels.

<table>
<thead>
<tr>
<th>Ice conditions</th>
<th>High pressure panel (Inerta)</th>
<th>Low pressure panel (Inerta)</th>
<th>Bow panel IB Otso (stainless steel)</th>
<th>Shoulder panel IB Otso (stainless steel)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level ice with dry snowcover</td>
<td>0.098</td>
<td>0.227</td>
<td>'86: 0.093 '87: 0.149</td>
<td>'86: 0.115 '87: 0.095</td>
</tr>
<tr>
<td>Level ice with wet snowcover</td>
<td>0.115</td>
<td>0.201</td>
<td>'86: 0.166 '87: 0.183</td>
<td>'86: 0.092</td>
</tr>
<tr>
<td>Level ice with water, sludge and snowcover (see figure 6)</td>
<td>0.076</td>
<td>0.204</td>
<td>'86: 0.168</td>
<td></td>
</tr>
<tr>
<td>Level ice (practically) without snow</td>
<td>0.073</td>
<td>0.168</td>
<td>'86: 0.092</td>
<td></td>
</tr>
<tr>
<td>Ridge</td>
<td>0.108</td>
<td>0.248</td>
<td>'86: 0.166 '87: 0.092</td>
<td></td>
</tr>
<tr>
<td>Own channel</td>
<td>0.100</td>
<td>0.199</td>
<td>'86: 0.183</td>
<td></td>
</tr>
<tr>
<td>Old channel</td>
<td>0.045</td>
<td>0.157</td>
<td>'86: 0.157</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 6: Cross section of level ice with water, sludge and snowcover.
3.2 Inerta coated steel and stainless steel

The full-scale friction panel measurements with the WARC testing bow and the IB Otso provided an opportunity to compare Inerta coated steel and stainless steel as the material of the icebreaker shell. As it can be seen from Table 1, the friction coefficients between ice and new Inerta coating and stainless steel are essentially of the same order of magnitude. In addition the measurements with the IB Otso in the winter of 1987 indicated that the friction coefficient of stainless steel did not increase after one year of icebreaker operation. Also, the experiences after the third service year of the IB Otso indicate that the wear resistance of stainless steel in ice conditions is much better than the wear resistance of Inerta and Inerta coated steel. Thus, by using stainless steel in the shell plating of an icebreaker, benefits in the ice resistance of an older ship and in the reduced need for maintenance are achieved. These benefits, however, need to be evaluated in the light of the higher initial building costs of the stainless steel coating.

3.3 Mean values of the friction coefficients measured in the model tests

The mean values of the friction coefficients measured for the model-scale friction panels both in the WARC testing bow and in the IB Otso with different model friction coefficients (ITTC) are collected in Table 2. In the same table the friction coefficients measured for the segments of the 2D-model are also presented.

<table>
<thead>
<tr>
<th>Ice condition</th>
<th>ITTC friction coeff.</th>
<th>High press. panel WARC testing bow</th>
<th>Low press. panel WARC testing bow</th>
<th>Low press. panel IB Otso</th>
<th>Bow panel IB Otso</th>
<th>Shoulder panel IB Otso</th>
<th>Segm. No 1 2D-model</th>
<th>Segm. No 2 2D-model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level ice</td>
<td>0.013</td>
<td>0.085</td>
<td>0.066</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.097</td>
<td>0.115</td>
<td>0.137</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.061</td>
<td>0.138</td>
<td>0.135</td>
<td>0.104</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.151</td>
<td>0.298</td>
<td>0.295</td>
<td>0.204</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.060</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.250</td>
<td>0.261</td>
</tr>
</tbody>
</table>
3.4 Friction test rig measurements; influence of water, snow, velocity and surface roughness on the friction coefficient

The influence of water, snow and velocity was investigated in the friction test rig measurements. The results of this investigation are shown in figure 7.

The influence of surface roughness was also investigated with the friction test rig by measuring the friction coefficient between ice and the following test plates:
- smooth steel, $\text{AHR} = 5 \mu m$
- sandplasted steel, $\text{AHR} = 127 \mu m$ The corroded steel plates were
- slightly corroded steel, $\text{AHR} = 600 \mu m$ cut out from the shell plating
- heavily corroded steel, $\text{AHR} = 1200 \mu m$ of an old icebreaker.
($\text{AHR} =$ Average Hull Roughness, measured with the BSRA Hull Roughness Analyser /11/)

The measured friction coefficient vs. the surface roughness is shown in figure 8.

Fig. 7: The influence of water, snow and velocity on the friction coefficient between ice and Inerta 160 /5/.

From figure 7 it can be seen that water on the clean ice decreases the friction coefficient from about 0.035 to 0.030, while snow on the ice increases the friction coefficient, dry snow to 0.10 and snow with water to 0.055. These results are parallel with the results measured in the field with friction panels in the WARC testing bow at front of the MS Protector (Table 1).
The radical increase of the friction coefficient with increasing surface roughness can be seen from figure 8. This depicts the development of the friction coefficient of the icebreaker shell with aging of the icebreaker.

3.5 Influence of speed on the friction coefficient

Based on the friction test rig measurements, the influence of the speed on the friction coefficient is ambiguous, as can be seen from figure 7. However, in the friction panel measurements in both full and model scales an increasing tendency of the friction coefficient with increasing ship speed was observed in many panels. A sample of this is shown in figure 9.

Fig. 9: The influence of the ship and model speed on the friction coefficient measured from the low pressure panel in the WARC testing bow.

One possible reason for the apparent discrepancy in the results obtained from the test rig and friction panel measurements is the - very likely speed dependent - water lubrication between ice and ship, which cannot be precisely simulated in the friction test rig measurements.

3.6 The influence of normal force on the friction coefficient

Many scientists, Oksanen /8/, Tatinclaux /9/ and Hoffmann /4/, for instance, have reported the ice friction to be as normal force or normal pressure dependent. A study of the normal force dependence of the friction coefficient was also made using regression analysis and based on these measurements. For the measured data regressions of the form

\[ \mu = a F_n^b + c \]  

were calculated. The form of the regression equation was chosen to fulfill both the theory of Oksanen, according to which

\[ \mu = a F_n^b \]  

and the theory of Tatinclaux, according to which

\[ F_t = k F_n + F_{to} \]
where: \[ \mu = \text{friction coefficient, defined as } \frac{F_t}{F_n} \]
\[ F_n = \text{normal force} \]
\[ F_t = \text{frictional force} \]
\[ a, b, c, k = \text{constants} \]
\[ F_{to} = \text{constant, essentially} > 0 \]

The calculated regression curves for both the full- and model-scale friction panel measurements are shown in figure 10.

In the calculated regression equations the constants \( a, b, \) and \( c \) for the full-scale panel results varied as follows: \( a \) from 0.12 to 0.54, \( b \) from -0.25 to -1.19 and \( c \) from 0 to 0.08, and for the model-scale results: \( a \) from 0.03 to 0.85, \( b \) from -0.65 to -1.56 and \( c \) from 0 to 0.13 depending on the model friction (ITTC). In many cases the constant \( b \) was close to -1 and the constant \( c \) was positive and differed from zero, which means that the results of these measurements support the theory of Tatinclaux rather than the theory of Oksanen.
4 COMPARISON OF MODEL- AND FULL-SCALE RESULTS

4.1 Comparison of the friction panel measurements

Full-scale / model-scale comparison of all friction panel measurements is shown in figure 11. The comparison is made as a function of the model friction coefficient (ITTC), and presented in the form where the value of the friction coefficient measured with each friction panel in model scale is presented as a percentage of the value measured with the corresponding panel in full scale. For example, in tests with the model friction coefficient (ITTC) of 0.061 the mean value of 0.138 of the friction coefficient for the low pressure panel of the IB Otso was measured (Table 2). In full scale for the corresponding panel the mean value of 0.093 of the friction coefficient was measured (Table 1). When 0.138 is 148% of 0.093, the point (0.061, 148) is plotted in figure 11. The points, marked with stars, are plotted in the figure in a similar way for each pair of model-scale / full-scale measurements. Linear inter- and extrapolation lines are drawn between the points. Thus, the intersection points between the 100%-level and the inter- and extrapolation lines for each friction panel comparison indicate the friction coefficient (ITTC) of the model, with which the best possible full-scale / model-scale correlation is achieved.

![Fig. 11: The full-scale / model-scale comparison of friction panel measurements.](image)

4.2 Ice resistances

The main target of many model test series is to predict the ice resistance of a prototype ship. This quantity is very much affected by the friction, both in model and in full scale. With respect to the reliability of the ice model tests, it is therefore interesting to compare the ice resistances of a ship measured in full scale with that predicted from model test results. A comparison for the WARC testing bow and the IB Otso based on model tests with various model friction coefficients (ITTC) is shown in figure 12.
Fig. 12: The full-scale / model-scale comparison of the ice resistances of the WARC testing bow (on the left) and the IB Otso.

The full-scale / model-scale comparison of the ice resistances is also presented in connection with the friction panel measurements in figure 11. From that figure it can be seen that the results of the full-scale / model-scale comparison of the ice resistances are in good harmony with the results of the friction panel measurements.

5 CONCLUSIONS

Measurements have shown that the friction coefficients between ice and a ship and also model ice and a model are affected by many parameters, such as snow, water, surface roughness and material of the shell plating and normal force or probably normal pressure. With respect to the friction modelling, the influence of many of these parameters can be taken into account by defining them very precisely according to the needs of the test series in question. For instance, if not otherwise stated, at WARC the full-scale predictions based on the ship model tests are made for a new ship with new Inerta 160 coating for ice conditions where there is a dry snowcover on the ice.

The normal force, or normal pressure, dependence of the friction coefficient is, however, more complicated to model than the influence of the other parameters because of the scale dependence of the normal force and the normal pressure. This may make the model friction coefficient scale dependent.

The study also indicated strongly that the best possible full-scale / model-scale correlation from the point of view of the friction modelling is achieved by using the model friction coefficient (ITTC) of 0.035-0.05. This model friction coefficient represents in full scale a new ship or a new off-shore structure with a new Inerta 160 or similar coating in level ice with dry snowcover. Also the full-scale / model-scale comparison of the ice resistances of the ships used in the tests supported the use of the model friction coefficient (ITTC) of 0.035-0.05.
6 ACKNOWLEDGEMENT

The financial support of the Technology Development Centre for both full- and model-scale measurements is gratefully acknowledged.

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AN ANALYSIS OF FACTORS INFLUENCING SHIP RESPONSE IN COLLISION WITH MULTI-YEAR ICE FLOES

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ABSTRACT

Collision with multi-year ice floes while navigating in the Arctic forms one of the hazards for structural integrity of ship hull. This paper contains an analysis of factors influencing ship hull bending moment due to collision with massive ice floes. First the theoretical model developed for the analysis is described. The ramming equations account for ship motions, ice crushing and elastic deformation. In the ramming the bow ice force is not known a priori and thus a kinematic condition must be used to solve the equations, which are nonlinear due to nonlinear dependency of crushing force on penetration into ice. The calculated results are compared with measured values from full scale tests with M.V. Arctic. The theoretical model is then used to investigate the influence of collision speed, hull parameters and bow shape on the hull response. The results are given for two ships: M.V. Arctic and the multi-purpose ship SA15. Also an analysis of the relative contribution of forces of various origins to the ramming process is given. The last part of the paper discusses the relationship between wave bending moment and the moment due to collision with ice.

1. INTRODUCTION

Essential basis for design of arctic vessels is by the mode of navigation. A merchant vessel may be designed based on two approaches: either the ship navigates independently or with the assistance of an icebreaker. The ship, which is navigating independently, must be capable to safely sail in all ice conditions to be encountered in the operation area.
The major factor influencing the safety is the strength of ship hull and machinery system. The strength of ship hull may be divided into three levels: shell plating, shell structure and hull girder. In this paper factors influencing ship hull strength are investigated. The topic is thus the longitudinal strength of an independently navigating arctic ship.

The experience of required longitudinal strength is limited to the observations from ships navigating in the Arctic, mainly from the multi-purpose ships SAl5 and M.V. Arctic. Some tests to ram multi-year ice have also been performed. When M.T. Manhattan passed through the North-West Passage in 1970 two ramming tests were made. In a ram with five knots on an ice floe of mass three times the ship displacement, a bending stress on deck of 80 MPa was measured [6].

In similar tests with M.V. Arctic a midship bending stress of 55 MPa in a ram with four knots was measured [2, 8]. Third ship used in ramming trials is Canmar Kigoriak. The measured bending stress here in a five knots ram was 35 MPa [3]. Both model scale and full scale tests showed that the maximum bending moment from ramming ice follows ramming speed linearly [8, 9, 10]. This observation leads to a question when the wave bending moment values are exceeded.

2. THE RAMMING SITUATION

The ice cover on the arctic seas consists of level and ridged first- and multiyear ice. The level first year ice can be up to two meters thick [16] and level multiyear ice about three metres thick [5]. First year ridges can be several tens of meters thick and thickness of multiyear ridges can exceed 10 metres [4].

The arctic areas where ships navigate are located on the edges of the Polar Pack. In these areas multiyear ice floes are encountered which are frozen into the first year ice cover during winter. As the first year ice cover is usually ridged, the multiyear floes are difficult to detect. Colliding with these floes forms the basic case for longitudinal strength evaluation of arctic vessels.

If the floe, which ship hits, is small, the collision force is determined by the motion of ice floe. The local strength may be exceeded in this case but not longitudinal strength. This is also the case if the floe is thin
enough to fail in bending. When the floe is both thick and large the ship response is greatest presenting biggest hazard for longitudinal strength. An ice floe which is thicker than about six meters and larger than five times the ship displacement may be considered infinite [8].

3. THEORETICAL MODELLING OF RAMMING

The situation under consideration is restricted to a case where the ship approaches from calm open water a massive ice floe the edge of which is rectangular. Ice is crushed in the collision and the ship bow slides onto the ice. The solution of the ramming problem consists of the normal force on stem \( F_n(t) \) and the hull bending moment and shear force \( M(x,t) \) and \( Q(x,t) \). The method presented here is described in more detail in ref. [8].

The solution of ramming is based on the displacement of the ship bow into ice, \( u_p \) and \( u_e \). The components are shown in fig. 1.

![Diagram of ice floe and ship displacement](image)

Figure 1. The displacement components in analyzing ramming.

As the bow force is not known a priori it must be determined from the condition that the ship bow is in contact with ice (bow force is zero if it is not). This kinematic condition may be expressed with the bow displacements as

\[ u_n = u_p + u_e \]

(1)

As all the displacements depend on the force \( F_n(t) \), it may be in principle solved from the kinematic condition. The problem is transferred to solving the displacement components. The left side of eq. (1) contains
the ship motion and right side the displacement of ice. Thus from the ship equations of motion \( u_h \) must be solved and from the equations covering ice deformation \( u_i \) and \( u_e \). If the floe is bent or moves as a rigid body, the corresponding displacement must be added into the kinematic condition.

The solution of the crushing penetration into ice is inferred from ice crushing tests. In these tests it has been observed that the average ice pressure in crushing is dependent on the apparent contact area as fig. 2 shows [12, 17].

![Test Configuration Diagram](image)

**Fig. 2.** The average ice pressure from two tests divided by the nominal ice pressure plotted versus the contact area. The lines drawn correspond to least squares regression [8].

These tests indicate that the average ice pressure can be assumed to be

\[
p_{av} = C_1 \lambda^2 p_{nom}, \quad \text{MAX} \quad p_{nom}
\]

Here \( C_1 \) and \( C_2 \) are empirical constants and the nominal ice pressure \( p_{nom} \) is the uniform ice pressure which breaks the ice in the contact geometry studied. It may be obtained by calculation geometry, see eg. references [8, 17]. The contact area is \( A \). For the ramming situation the constants are assumed to be \( C_1 = 0.3 \) and \( C_2 = -0.4 \) (unit meter). The nominal ice pressure has been calculated for this geometry giving \( p_{nom} = 8.4 \) MPa and \( p_{nom} = 14.2 \) MPa for ice temperatures of \(-2^\circ C\) and \(-10^\circ C\). In the subsequent
calculations a value \( p_{\text{nom}} = 11.3 \) MPa is used corresponding to temperature \(-6\) °C. Now the relationship between bow force and crushing penetration is

\[
F_n(t) = \frac{\tan \beta}{\tan \alpha + \sin \varphi} \quad p_{av} \lambda = \frac{\tan \beta}{\sin^2 \varphi \cos \varphi} \quad p_{av} \quad u_p^2(t) \quad (3)
\]

where \( \alpha \) is half of the waterline entrance angle and \( \varphi \) stem angle.

The elastic displacement of ice, \( u_e \), is small, some millimeters. It influences, however, much the interaction between ship and ice. An adequate definition of this displacement for ramming case follows the Boussinesq solution for semi-infinite body where the elastic displacement is directly proportional to contact pressure and contact area divided by contact diameter and inversely proportional to Young's modulus. The constant of proportionality must be obtained for each case by calculation. For the ramming case it has been calculated, \( C = 0.26 \) [8]. Thus, if instead of contact diameter the contact is scaled by crushing depth, then

\[
u_e = C \sqrt{\frac{\tan^2 \alpha + \sin^2 \varphi}{\tan \alpha}} \quad \frac{F_n(t)}{E \quad u_p^2(t)} \quad (4)
\]

where \( E \) is Young's modulus of ice, assumed isotropic. It's value in calculations is \( 6.7 \) GPa.

The ship motions in symmetric ramming case are in \( xz \)-plane. Thus the bow motion may be divided into two components in \( x \)- and \( z \)-directions \( u_x \) and \( u_z \). For these the equations of motion are readily derived, see [8]. In ramming case the equation for \( u_x \) contains only the inertial term and horizontal force \( F_x \). The vertical bow motion consists of contributions from heave, pitch and hull bending. Here the solution may be accomplished by mode superposition technique [1, 8]. Fig. 3 illustrates the quantities used in the analysis of ship motion.

Once the vertical and horizontal displacements are solved, the normal bow motion is given by

\[
u_n = \sin \varphi \quad u_x - \cos \varphi \quad u_z \quad (5)
\]

The bow force could be solved directly for every time instant from the kinematic condition using eqs. (3), (4) and the ship equations of motion.
This results, however, in an implicit and nonlinear equation for the force. Implicit because solving ship equations of motion results in integration and nonlinear because the relationships between ice displacements and force (eqs. (3) and (4)) are nonlinear. Consequently it must be solved numerically. One alternative now is to discretize time and assume force linear within each time step,

\[ F_n(t) = F_n(t_0) + b(t - t_0), \quad t_0 \leq t \leq t_0 + \Delta t \]  

(5)

This results in an algorithm in which the starting point is \( F_n(0) = 0 \) and \( b \) must be solved for each time step from the kinematic condition. The equation for \( b \) is nonlinear and must be solved numerically. Once the constant \( b \) is solved, the ship response is obtained from the equations of motion. The time step used should be at maximum half of the period of the highest natural mode included.

The calculation has three branches: crushing and sliding, solely sliding and free motion. This is a result from physical restrictions:
- the contact force \( F_n(t) \) and thus the elastic displacement of ice \( u_e(t) \) is always non-negative
- during sliding motion the crushing depth \( u_p \) stays constant
- the friction force \( F_p = \mu F_n \) opposes the motion.

The initial values for calculation are the values of displacements and forces before the ram. All these are zero except \( u_x(0) \) which is the ramming speed.
3. RESULTS OF CALCULATIONS

The results of calculations are illustrated using two ships. These are M.V. Arctic and a multi-purpose ship of type SA-15. The displacement of these ships is 38030 t and 23550 t respectively. The ships are described in more detail in references [8, 18]. Results of ramming simulation for the two ships are shown in fig. 4.

![Graph of SA-15 v = 4 knots](image)

![Graph of M.V. Arctic v = 4 knots](image)

Fig. 4. Results of ramming simulation for the two example ships.

Both the rams contain similar phases: first the ship crushes ice having at the same time tangential motion till the direction of velocity of bow is along the stem. Then the sliding phase starts and the bow force drops. The sliding phase is followed by a crushing phase when the direction of the bow velocity is towards ice. These phases can alternate until the ship starts to slide back. One of the more noticeable features of time histories of hull bending moment of bow force that they contain frequency components,
which do not correspond to ship natural frequencies. These frequencies for M.V. Arctic are about 0.5 and 1.5 Hz whereas the pitching frequency is 0.15 Hz and first bending frequency 0.9 Hz [2, 8]. These frequencies can be seen also in full scale measurements, see fig. 5. The calculation for both ships was performed using 12 first natural modes. A study revealed, however, that the simulation was not influenced noticeably by the number of modes included after about the seventh mode.

Fig. 5. Measured and calculated time history and Fourier spectra of bow ice force and hull bending moment [8].

It may be of interest to compare the calculated values with the values obtained from full scale. Fig. 6 shows such a comparison: the maximum values of vertical bow force, bending moment and crushing depth are plotted versus the ramming speed. The apparently good fit is made more understandable when it is remembered that the equation for average ice pressure (eq. (2)) was partly derived from these tests.
Fig. 6. Comparison between calculated and measured maximum crushing depths, vertical bow forces and hull bending moments for M.V. Arctic plotted versus ramming speed.

One of the advantages of a simulation model as compared to e.g. model tests is that parametric studies can numerically be made with small effort. Here the influence of bow shape and ice characteristics is studied by variation of bow angles $\alpha$ and nominal ice pressure $p_{nom}$, dependency of average ice pressure on contact area $C_2$ and the coefficient of friction $\mu$. The variation is done for a ram of 4 knots keeping the other parameters fixed. The results of the parametric study for the two ships is shown in fig. 7.

The bow shape has only a slight influence on the ship response: the blunter the waterline is the higher the hull bending moment is. The stem angle has, however, an opposite influence on hull response. Also the ice characteristics influence the response relatively little. These conclusions indicate that the ramming is mainly influenced by ship main particulars.
Fig. 7. Results of variation of parameters describing bow shape or ice characteristics. The maximum vertical bow force and hull bending moment is considered for two ships.
4. ANALYSIS OF RAMMING

More insight of the relative importance of forces of different origin may be gained if the corresponding energies are considered during a ram. Here these energies are divided into contribution from kinetic energy in x- and z-directions \( T_x \) and \( T_z \), potential energy \( V \), energies consumed in crushing ice \( E_{cr} \), sliding on ice \( E_{sl} \), and hydrodynamic damping \( E_{damp} \). Fig. 8 shows results of energy breakdown for M.V. Arctic rams with 2.5 and 5 knots. The values shown are presented relative to the initial total mechanical energy. The small contribution of kinetic energy in z-direction is to be noticed. Ramming can be described to be an exchange of initial kinetic energy to potential energy of bow rise, and its consumption in ice crushing and sliding. About 35% of the initial total mechanical energy is consumed in crushing the ice. The ice strength influences only the crushing and thus its small influence on ship response is understandable. This conclusion has also been made from model tests [11].

![Energy Breakdown Diagram](image)

Fig. 8. The breakdown of energies involved in ramming calculated using two speeds for M.V. Arctic.

5. LONGITUDINAL STRENGTH IN ICE

The question whether the ramming situation is relevant in ship design may be considered comparing hull bending moments encountered in open water and in ramming ice. The comparison is performed here for M.V. Arctic and SA-15. As the main parameter in ramming is ship speed, it is used as a parameter calculating the ice moment. This is compared with design wave bending moments of three classification societies: USSR Register of Shipping [13], Det norske Veritas [14] and Lloyd's Register of Shipping [15] and the
directly estimated bending moment of probability level $10^{-8}$ [7]. The results of comparison are shown in fig. 9.

![M.V. Arctic Graph](image)

![SA-15 Graph](image)

Fig. 9. The maximum hull bending moment ramming ice compared with rule wave bending moment.

Fig. 9 shows that the wave bending moment is exceeded if the ships ram massive ice floes with a speed of about 8 knots. The differences in wave bending moments is due to differences in design stresses and safety factors which the classification societies use.

Merchant vessel, which is designed for independent navigation in the Arctic, should be able to move in first year ridge fields. The velocity of ship comes close to open water values in such ridge fields for instance when the ice conditions get lighter e.g. between ridges. As the observation of multiyear ridges in ridge fields is difficult, collisions with multiyear floes may occur with speeds that hazard the longitudinal strength. If, on
the other hand, the ship speed in ice is restricted, the ice navigation capability deteriorates.

6. CONCLUSIONS

The collision between a ship and a multi year ice floe may be analyzed using a theoretical simulation model. The model described accounts for ship hull bending, ship rigid body motions, ice crushing and elastic deformation and the frictional forces. The results of calculations compare fairly well with values measured in full scale. The future development of the theoretical model should be directed towards including a finite size or thickness of ice floe or allowing for an unsymmetric ram.

The longitudinal strength of ships judged with hull bending moment is the same in ice (allowing for ramming) and open water if the maximum speed in ice is restricted to about 8 knots. Whether this is an active constraint or not cannot be answered by solely ramming simulation. The detection and avoidance of multi year floes as well as the occurrence of them must also be considered. This paper does not at all touch the question of relating the ship main dimensions and the maximum bending moment or stress. This problem should be the next step in the evaluation of the longitudinal strength of arctic ships.

ACKNOWLEDGEMENTS

This work was made possible by the funding from The Technology Development Centre of Finland and The Winter Navigation Research Board. This support is gratefully acknowledged. Without the demanding and encouraging atmosphere in the Laboratory of Naval Architecture and Marine Engineering this study would not have come about.

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3. Ghoneim, G. & al., Global ship ice impact forces determined from full-scale tests and analytical modelling of the icebreakers Canmar Kigoriak


MISSION-BASED APPROACH IN MODERN ICEBREAKER DESIGN

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Wartsila Arctic Research Centre  
Director  
Helsinki, Finland

ABSTRACT

Assessments of the capabilities of icebreakers are often focused on only a small number of operational parameters. This paper presents a method for studying all the relevant parameters. The method starts with a careful definition of the mission profile, and should result in a well-balanced design. The usefulness of model testing is studied as a starting-point for economic calculations. The economy of two designs is considered for a Baltic mission profile, and the effect of breadth combinations is studied for the total system of icebreaker and assisted merchant vessel.

1. INTRODUCTION

The classical way of comparing icebreakers and specifying their capabilities has been simply to define their power. The users had in mind the power they needed for a specific icebreaking task, and this gave a good enough picture of the capability as long as the development of icebreakers was fairly stable.

A change came with the emergence of the new low-resistance bow type. In measure effectiveness attention became focused on reduction of ice resistance or maximization of icebreaking capability. The concurrent use of a propeller nozzle further increased the icebreaking capability. Today, the trend seems to be to overemphasize the importance of maximizing level icebreaking capability, regardless of the mission profile of the vessel. This is somewhat analogous to basing a comparison of cars solely on their maximum speed.

An alternative approach is to start from the mission profile of the vessel. In this approach, the design takes account of all the important
operational aspects. The maximum icebreaking capability is usually one of the most important, but other features should not be sacrificed to it.

2. MISSION PROFILE ANALYSIS

It is essential to the success of any ship design to define the mission profile and the operational environment as clearly as possible. The future development of the profile (Ref.1) should be considered as well. The various factors can be categorized as follows:

THE PURPOSE OF THE VESSEL

- escort duties
- size and power distribution of the escorted vessels
- other duties, such as offshore support, rescue, research and so on
- other icebreakers that will operate with the vessel
- seasonal use

RANGE

- typical range of voyages and the fuel economy required

ENVIRONMENT

- ice conditions
  - level ice thickness and strength
  - dynamics of the ice - wind and current
  - ridge distribution and thickness
  - typical snow cover
- open water/ice duty distribution
- open water sea state distribution
- shallow water restrictions

A set of operational requirements for the design can now be constructed. They can be, for example: level ice icebreaking capability ahead and astern, performance in ice pressure ahead and astern, ridge breaking capability, manoeuvrability, seakeeping qualities and so on. Two or more designs can then be compared against these requirements. To make the comparison less subjective, it should be quantified with the aid of a scale, say from 0 to 5, from very poor to excellent. The grading should of course be based on as accurate information as possible: calculations and
model or full-scale test results.

It is also necessary to access the relative importance of the various operational requirements by considering the mission and environment. Again, the relative importance can be quantified with a scale from 0 to 5, from negligible to very important. This can best be done by careful discussion with the users - the masters of vessels in the same or similar service.

Finally, the values may be multiplied by each other for each requirement. By taking the total score for each vessel, a ranking list can then be compiled up (Table 1.)

Table 1. Comparison table of two designs vs operational requirements

<table>
<thead>
<tr>
<th>Escort Icebreaking on Certain Duty</th>
<th>Relative Importance</th>
<th>Design 1</th>
<th>Design 2</th>
<th>Weighted Comparison Design 1</th>
<th>Weighted Comparison Design 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level Ice Ahead</td>
<td>4</td>
<td>3</td>
<td>4</td>
<td>12</td>
<td>16</td>
</tr>
<tr>
<td>Thick Channel Ahead</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>9</td>
<td>12</td>
</tr>
<tr>
<td>Ridge Ahead</td>
<td>4</td>
<td>2</td>
<td>4</td>
<td>8</td>
<td>16</td>
</tr>
<tr>
<td>Level Ice Astern</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Thick Channel Astern</td>
<td>3</td>
<td>4</td>
<td>4</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>Ridge Astern</td>
<td>2</td>
<td>4</td>
<td>4</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Turning Diameter</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>12</td>
<td>15</td>
</tr>
<tr>
<td>Herring Bone Turn</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>9</td>
<td>12</td>
</tr>
<tr>
<td>Outbreaking of Channel</td>
<td>3</td>
<td>2</td>
<td>4</td>
<td>9</td>
<td>12</td>
</tr>
<tr>
<td>Channel Clearance</td>
<td>3</td>
<td>2</td>
<td>4</td>
<td>6</td>
<td>12</td>
</tr>
<tr>
<td>Channel Breadth</td>
<td>4</td>
<td>2</td>
<td>3</td>
<td>8</td>
<td>12</td>
</tr>
<tr>
<td>Ice Pressure Ahead</td>
<td>5</td>
<td>4</td>
<td>3</td>
<td>20</td>
<td>15</td>
</tr>
<tr>
<td>Ice Pressure Astern</td>
<td>5</td>
<td>4</td>
<td>3</td>
<td>20</td>
<td>15</td>
</tr>
<tr>
<td>Shallow Water Performance</td>
<td>1</td>
<td>2</td>
<td>4</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Seakeeping</td>
<td>2</td>
<td>4</td>
<td>3</td>
<td>6</td>
<td>183</td>
</tr>
</tbody>
</table>

In this example design 2 is clearly better. Design 1 is a fairly conventional design whereas design 2 has a low resistance bow. It has to be remembered that the relative importance given for various requirements is not general for any escort icebreaker - it is valid only for a certain duty that in this case is escorting mainly at Kara Sea.
This method can be criticized for its roughness, and it can also be claimed that the result can be manipulated, by selective grading. Manipulation can be avoided by choosing the relative importance values together with the owners and, as already mentioned, the values awarded in the comparison of the designs should be based on calculations, model test results or full-scale results. In any case, this method is better than that of pinpointing a few of the important requirements - perhaps also selected by manipulation. This method can reveal the unfavourable effects that some extremely desirable factor may have on another, and thus give a more balanced end result.

3. ECONOMIC COMPARISON

A comparison based purely on operational aspects and the technical capability to fulfil the various requirements may lead to an uneconomical solution. Therefore the various designs should be compared economically as well. The capital cost is the most obvious one. But the running costs of the vessels are also important, the chief of these being the manning and fuel costs. The estimate of the fuel costs is based on the operational profile and the duties of the vessel. The running costs for the economic life of the vessel should be discounted to obtain the net present value of the project. Another way is to calculate the annuity of the capital cost and get the annual average cost. The required charter rate per day can then also be calculated.

The usefulness of model testing as a source of input values for the economic calculations is studied in the following example. A model test series performed in WARC for two icebreaker designs is used. The comparison is made for Baltic escort duties.

The main dimensions of the vessels are shown in Table 2, and are indicative of typical Baltic twin screw escort icebreakers. Vessel 1 is a typical "barge bow" design - with nozzles and mechanical drive and Vessel 2 has a more conventional hull shape, and open propellers with AC-AC drive.

Table 2. The main characteristics of the model tested designs

<table>
<thead>
<tr>
<th></th>
<th>Vessel 1</th>
<th>Vessel 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>LWL/m</td>
<td>96.0</td>
<td>90.0</td>
</tr>
<tr>
<td>BWL/m</td>
<td>29.4</td>
<td>23.4</td>
</tr>
<tr>
<td>TWL/m</td>
<td>8.0</td>
<td>7.3</td>
</tr>
<tr>
<td>Pd/kW</td>
<td>18000</td>
<td>15000</td>
</tr>
<tr>
<td>Bollard pull/kN</td>
<td>2500</td>
<td>1600</td>
</tr>
</tbody>
</table>
The main results of the model tests are shown in Figure 1 (speed versus ice thickness with full power).

Vessel 1 can be seen to have a better capacity in thick ice, whereas Vessel 2 is faster in the normal Baltic ice thickness of 0.6 to 0.9 m.

Let us consider what this means on a typical trip of 110 nautical miles (equivalent of the distance from Kvarken - Mid Bothnian Bay - to Luleå). If the ice thickness is 0.8 m, Vessel 1 will complete the trip in 14.9 hours and Vessel 2 in 12.6 hours. For Vessel 1 the efficiency from diesel to propeller is defined as $\eta = 0.95$ and for Vessel 2 as $\eta = 0.91$. Using the specific fuel consumption of 185 g/kWh, for both diesels we find that Vessel 1 needs 52 tons fuel for the trip and Vessel 2 needs 38 tons. Since the vessels are intended for escorting, account must also be taken of the breadth of the channel provided. This can be done by taking as measure the miles of for example 25-m-broad channel provided per ton fuel. In our example, this value is 2.48 for Vessel 1 and 2.68 for Vessel 2.

To obtain a rough idea of the effect of the difference in speed vs. ice thickness on the total fuel economy, the mission profile for the whole year is considered. The values for a typical Baltic icebreaker are given in Table 3.
Table 3. A typical yearly power profile for Baltic icebreakers

<table>
<thead>
<tr>
<th></th>
<th>Time</th>
<th>Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ice navigation (level ice or channel)</td>
<td>1500 h</td>
<td>75% MCR</td>
</tr>
<tr>
<td>Ice navigation (ridges, tow)</td>
<td>600 h</td>
<td>100% MCR</td>
</tr>
<tr>
<td>Transit</td>
<td>400 h</td>
<td>50% MCR</td>
</tr>
<tr>
<td>Idle, harbour</td>
<td>2200 h</td>
<td></td>
</tr>
</tbody>
</table>

This table is considered to be valid for Vessel 2. A simple method would be to use it without modification for Vessel 1 as well. Another approach is to take as starting points the speed/ice thickness combinations that are got from the Table 2 power levels for Vessel 2 in the ice navigation period. The equivalent power for Vessel 1 is then calculated for the same operational points. Thus we obtain equal performance for the two vessels. In the calculations a nozzle of type 37 is used for Vessel 1. The power levels are then as follows:

Table 4. Power levels needed for equal performance for both compared designs

<table>
<thead>
<tr>
<th></th>
<th>Vessel 2</th>
<th>Vessel 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ice navigation (level ice)</td>
<td>11.25 MW</td>
<td>corresponding to v=4.0m/s h_ice=0.8 m</td>
</tr>
<tr>
<td>Ice navigation (ridges, tow)</td>
<td>15.0 MW</td>
<td>corresponding to v=1.0m/s</td>
</tr>
<tr>
<td>Transit</td>
<td>7.5 MW</td>
<td>9.0 MW</td>
</tr>
</tbody>
</table>

Auxiliary power of 1.5 MW is used for both vessels. In harbour this decreases to 0.5 MW. The total fuel consumption for Vessel 1 is 7300 tons HFO, 970 tons DO and for Vessel 2 6600 tons HFO and 220 tons DO. Using the prices of 135 USD/ton for HFO and 200 USD/ton for DO (November 1988) we obtain a yearly fuel cost of 1.18 MUSD for Vessel 1 and 0.95 MUSD for Vessel 2. The effect of the accuracy of the original model test results may be examined; if the speed of Vessel 1 in 0.8 m thick ice was 10% higher, the annual consumption of HFO would be roughly 730 t lower and accordingly the yearly fuel bill would be 1.08 MUSD.

4. TOTAL OPERATIONAL ECONOMICS OF THE SYSTEM

In the previous section, the economic measures of merit were discussed. In the case of an escort icebreaker, the total system should be considered:
the assisted vessel or fleet as well as the icebreaker. This is of course a somewhat academic approach if the merchant vessel and icebreaker do not have the same owner. The owner looks strictly for the most economical solution to his problem, but if the optimum for the total traffic is sought, the system should be considered in its entirety. The ultimate criterion should therefore be the tons of fuel oil needed for transportation of a certain amount of cargo. The relevant parameters affecting the results are:

- environmental - ice conditions on the route
- operational - assistance by towing or not
- technical - ice resistance encountered by merchant vessels and icebreaker in various environmental conditions, channel clearance and the breadth combination of the vessels.

Transit simulation calculations for certain ice routes have been made on a fairly routine basis to optimize merchant vessel design. In these comparisons, the icebreakers are usually left out of account, but at least one published exception exists (Ref.2). In those calculations the treatment was rather rough, the total cost of the cargo transported was estimated with and without icebreaker assistance.

As a step towards fleet optimization, an attempt was made to study the effect of icebreaker breadth, using model testing technique for certain Baltic ice conditions. Model tests in ice have traditionally been resistance, propulsion and manoeuvring tests, but a more operative approach was used in these tests. In particular the simulation of ice pressure due to wind is a technique not published earlier. The tests were made in WARC in 1987 and 1988. A combination of two icebreakers and three merchant vessels was selected. The smaller icebreaker represented the Otso class (B=23.35 m) and the larger icebreaker had a similar hull form, but a beam of B=28.0 m. The merchant vessels assisted were of poor icebreaking shape - all had the same bow form. The breadth range extended on both sides of the beams of the icebreakers - the maximum being 34.4 m, which can be considered very rare in the Baltic in wintertime.

The merchant vessels were towed without their own propulsion by a short tow (5 m in full scale), figure 2. Thus the effect on channel clearance of the different icebreaker forms is more or less eliminated. The iceconditions simulated were rafted 0.8 - 1.0 m thick ice consisting of two layers. WARC FG-ice of 400 kPa flexural strength (in full scale) was used. The tests were run both with and without simulated ice pressure due to wind (~50 kN/m). The main parameter measured was the towing force.
The main result is presented in figure 3. Further calculations were made for the case in which the merchant vessels used their own propulsion. The power for each vessel was selected from size/power statistics. The total power as a function of merchant vessel breadth is presented in figure 4. The conclusion to be drawn from these tests is that in the tested conditions the greater icebreaker beam does not decrease the tow force enough to decrease the total power needed.
5. CONCLUSIONS

Icebreaker design has been considered from three different points of view. The first approach is a technical evaluation based on the mission profile and the relative importance of the operational requirements. Although the method is rough, it can elucidate the problem from different angles and give a balanced result. The second approach is to consider the economics of the vessel and the third is to study the economics of the whole system.

Model testing is presented as the starting-point for the calculations. The examples show the new aspects that can be elucidated especially well by operational model tests. The results of the case studies show that high icebreaking capability in thick ice, due to low ice resistance, is not necessarily beneficial in the typical thinner Baltic ice thicknesses or at higher speeds. Thus the economic performance of this design is inferior to that of the design with higher speed in thin ice. The breadth combinations studied show that increasing the icebreaker breadth does not decrease the total energy used by the icebreaker and merchant vessel in the tested ice conditions.

6. ACKNOWLEDGEMENTS

Thanks are due to the Finnish Board of Navigation for its valuable contribution to the operational model tests.
7. REFERENCES


MODEL TESTS ON AN ICEBREAKER AT TWO FRICTION FACTORS

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ABSTRACT

Results of resistance and propulsion tests in level ice of a model of the Canadian R-class icebreaker for two values of the ice-hull friction factor are presented. The increase in ice resistance due to increased ice friction was significant for thick, weak ice, but negligible in thin and strong ice. Also, the increase in the friction factor had no detectable effect on propeller performance. Ice-propeller interaction had little effect on the model thrust coefficient, but a strong one on the torque coefficient and the average thrust deduction factor. Comparison of the test results with full-scale trial data showed that ice-propeller interaction was more severe at model scale than at full scale for ice thickness up to about 0.7 m. For thicker ice, model and field data were in very good agreement.

1. INTRODUCTION

This paper presents a summary of the results of resistance and propulsion tests in level ice performed at the Cold Regions Research and Engineering Laboratory (CRREL) of the U.S. Army Corps of Engineers on a smooth and a roughened 1:20 scale model of the Canadian R-Class icebreaker (Tatinclaux, 1984; Tatinclaux and Martinson, in press). The Canadian R-class icebreaker was designed to operate continuously at 3 kts in 1 m of level ice. The main hull and propeller characteristics at full and model scales are listed in Table 1.

Comparison of the test results with available full-scale trials data (Edwards et al. 1981, Michailidis and Murdey 1981) is presented. CRREL

774
was a participant in the comparative program organized by the Performance in Ice-Covered Waters Committee (Ice Committee for short) of the International Towing Tank Conference (ITTC 1984 and 1987), which is preparing an analysis of the results obtained at the various participating facilities.

Table 1. Main characteristics of R-class icebreaker

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Full scale</th>
<th>1:20 model</th>
</tr>
</thead>
<tbody>
<tr>
<td>LWL Length at waterline</td>
<td>93 m</td>
<td>4.65 m</td>
</tr>
<tr>
<td>Lpp Length between perpendiculars</td>
<td>87.96 m</td>
<td>4.40 m</td>
</tr>
<tr>
<td>T Level draft</td>
<td>6.94 m</td>
<td>0.35 m</td>
</tr>
<tr>
<td>B Maximum waterline beam</td>
<td>19.37 m</td>
<td>0.97 m</td>
</tr>
<tr>
<td>Displacement</td>
<td>7630 m³</td>
<td>0.95 m³</td>
</tr>
<tr>
<td>CB Block coefficient</td>
<td>0.611</td>
<td></td>
</tr>
<tr>
<td>Qmax Maximum section coefficient</td>
<td></td>
<td>0.918</td>
</tr>
<tr>
<td>Cp Prismatic coefficient</td>
<td>0.665</td>
<td></td>
</tr>
<tr>
<td>Ow Waterplane area coefficient</td>
<td>0.799</td>
<td></td>
</tr>
<tr>
<td>Number of propellers</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Number of blades per propeller</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>D Propeller diameter</td>
<td>4.12 m</td>
<td>0.206 m</td>
</tr>
<tr>
<td>Pitch/diameter ratio</td>
<td></td>
<td>0.670</td>
</tr>
<tr>
<td>Installed power</td>
<td>11,000 kW</td>
<td></td>
</tr>
</tbody>
</table>

2. TEST CONDITIONS

The conditions set by the ITTC Ice Committee for the resistance and propulsion tests with the 1:20 scale model are given in Table 2. The actual conditions of the tests reported here were ice thickness of 20 to 40 mm, and 17 to 44 mm for the smooth and roughened model, respectively, ice strength of 25 to 55 kPa, and 20 to 60 kPa, respectively, and velocity of 0.1 to 1.24 m/s for both models.

The urea-doped ice used in the CRREL Test Basin is grown at -20°C from a 1% solution by weight of carbamide in water and tempered at about 0°C until the target ice strength is nearly reached.
Table 2. Test conditions

<table>
<thead>
<tr>
<th></th>
<th>Full scale</th>
<th>Model scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ice thickness h</td>
<td>45 and 70 cm</td>
<td>22.5 and 35 mm</td>
</tr>
<tr>
<td>Ice strength G</td>
<td>400 and 800 kPa</td>
<td>20 and 40 kPa</td>
</tr>
<tr>
<td>Ship speed V</td>
<td>0.5 to 5.0 m/s</td>
<td>0.11 to 1.12 m/s</td>
</tr>
</tbody>
</table>

range of $F_n$ 0.2 to 2.4
range of $C_n$ 60 to 180

3. ICE-HULL FRICTION FACTOR

The friction factor was determined by measuring the force $F_T$ necessary to pull an ice sample horizontally over either the model hull or a test plate at a constant speed (10 cm/s) and under a total load $F_N$. The apparent friction coefficient $f_a$ was calculated as

$$ f_a = \frac{F_T}{F_N} $$

For the smooth model the normal load was kept constant and the value of $f_a$ was found to be $0.041 \pm 0.004$. For the rough model, the normal load was varied to achieve a normal pressure from 1 to 4 kPa. The average value of $f_a$ was found to be $0.086 \pm 0.026$, but $f_a$ was observed to decrease with increasing normal pressure. However, $F_T$ was found to be a linear function of $F_N$

$$ F_T = f_i F_N + T_o $$

where $f_i$ was interpreted as the true friction factor. Linear regression analysis of the test data yielded $T_o = 0.62$ N and $f_i = 0.065$.

No reliable full-scale measurements of $f_i$ is known to this writer at this time.

4. RESISTANCE

4.1 Experimental procedures

In the resistance tests, the ship model was connected to the towing carriage by a rigid 7.5-cm (3-in.) diameter towing post and was
restrained in surge and sway but free to heave, pitch and roll. Once an ice sheet had reached the desired thickness $h$ and strength, three tests were made at different velocities $V$, each over a distance of about 10 m (two model lengths). The total ice resistance $R_{it}$ was measured, and the net ice resistance was then calculated as $R_i = R_{it} - R_{ow}$, where $R_{ow}$ is the resistance in clear water estimated from the test results by Murdey (1980). Except at relatively high speed in thin ice, the clear water resistance is usually very small as compared to the net ice resistance and well within the range of uncertainty of $R_{it}$.

4.2 Data Analysis

As is customary, the nondimensional ice resistance, $R_t = R_{it}/\sqrt{gh}$ or $R_n = R_i/\sqrt{gh}$, was considered to be primarily a function of the Froude number $F_n = V/\sqrt{gh}$, and of the nondimensional ice strength $C_n = \sigma/\sqrt{gh}$, where $B$ is the beam at the waterline and $\sigma$ is the water specific weight, and was assumed to be a linear function of $C_n$ and a second degree polynomial in $F_n$. The following regression equations and corresponding correlation coefficients were obtained.

For the smooth model

\begin{align*}
R_t &= 0.07 + 0.92 F_n + 1.46 F_n^2 + 0.038 C_n \quad (r=0.98) \\
R_n &= 0.19 + 1.09 F_n + 0.78 F_n^2 + 0.036 C_n \quad (r=0.97)
\end{align*}

For the rough model

\begin{align*}
R_t &= 2.68 + 2.50 F_n + 1.00 F_n^2 + 0.017 C_n \quad (r=0.96) \\
R_n &= 2.74 + 2.91 F_n + 0.22 F_n^2 + 0.016 C_n \quad (r=0.94)
\end{align*}

All are valid only for the test range of the variables, namely $0.17 < F_n < 2.6$, and $60 < C_n < 200$.

The test data and regression curves for the extreme values of $C_n$ are shown on Figure 1. At $C_n = 60$, the roughened model exhibits a higher resistance than the smooth model, as expected, but at $C_n = 200$ both models have nearly the same resistance. This would indicate that for the stronger and thinner ice, the friction component of the resistance is small compared to the ice breaking and ice submergence components.
5. PROPULSION TESTS

5.1 Experimental setup and procedure

For the propulsion tests, each propeller shaft was mounted with a thrust and torque dynamometer, rated at 1100 N in thrust and 11.3 Nm in torque. Both shafts were driven by a single 745-W (1-hp) variable speed electric DC-motor equipped with a tachometer feedback to maintain the rotational speed at the set value. The shaft speed was measured by a magnetic pickup mounted over a 60-tooth gear fastened to the portside propeller shaft. Seven data channels were scanned and sampled: carriage speed (v), force block (pull), propeller speed (n), and thrust (T) and torque (Q) of both propellers. The analog signals from the force block, the thrust and torque outputs of one dynamometer, and the propeller speed counter were monitored on a chart recorder to ensure visually that all systems were functioning.

All propulsion tests were made by the captive model technique. In each ice sheet, three tests were made at the same carriage speed but for three propeller speeds. Bollard tests were made at the beginning and the end of each propulsion test to check the proper functioning of the dynamometers. In addition to the tests in ice, propulsion tests were made in clear water for comparison with the test results reported by Murdey (1980).
5.2 Data analysis and presentation

The results of the three tests performed at a given carriage velocity in one ice sheet were interpolated to the point of zero pull to obtain the self-propulsion point for the corresponding ice thickness, ice strength and ship speed. The propulsion characteristics, thrust and torque coefficients, $K_t$ and $K_q$, and thrust deduction factor, $t$, were calculated

\[
K_t = \frac{T}{\frac{1}{2} \rho n^2 D^4}
\]

\[
K_q = \frac{Q}{\frac{1}{2} \rho n^2 D^5}
\]

\[
t = 1 - \frac{R_p}{T}
\]

where $D$ is the propeller diameter, $\rho$ the water density and $R_p$ is the total resistance given by eq. 3a and 4a for the particular test conditions. The accuracy of $t$ depends mainly on that of the resistance estimate, at best $\pm 10\%$ of the mean value, and even if the propeller thrusts are accurately measured, significant uncertainties on $t$ will remain.

The thrust and torque coefficients, $K_t$ and $K_q$, from propulsion tests both in level ice and in ice-free water are plotted versus $J_a = V/nD$, the apparent advance coefficient on Figure 2. It can be seen that the thrust coefficient for the rougher model in level ice is only slightly smaller than in ice-free water. That for the smooth model was higher than $K_t$ for both the rougher model and the ice-free conditions, which indicated inaccuracies or malfunction of the thrust dynamometers, or both, during the tests with the smooth model. In the following analyses and full-scale extrapolations, the values of $K_t$ obtained from the propulsion tests with the rougher model were assumed valid for the smooth model, since the values of $K_q$ obtained with both models are comparable, practically constant and consistently greater than for the ice-free conditions. The changes in $K_t$ and $K_q$ between level ice and ice-free conditions are attributed to ingestion of ice floes by the propellers, which results in an increase of the torque on the propellers and a decrease in the thrust delivered by the propellers. The following equations were obtained.
For clear water conditions

\[
K_t = 0.339 - 0.303 \, J_a \quad (r = 0.986) \quad (6)
\]

\[
K_q = 0.0402 - 0.0308 \, J_a \quad (r = 0.969) \quad (7)
\]

For level ice conditions with both models

\[
K_t = 0.339 - 0.318 \, J_a \quad (r = 0.972) \quad (8)
\]

\[
K_q = 0.0402 - 0.0066 \, J_a \quad (r = 0.38) \quad (9)
\]

Figure 2. Model propeller characteristics in level ice
Figure 3 gives the values of t at the self-propulsion points of the roughened model, those obtained by Murdey (1980) in clear water, and those evaluated from the results of Murdey's overload tests in clear water for the conditions of model speed and propeller speed corresponding to the self-propulsion points in ice. It can be seen that the values of t in level ice are scattered about those in clear water.

![Graph showing thrust deduction factor](image)

**Figure 3. Thrust deduction factor**

6. FULL-SCALE PREDICTIONS AND COMPARISON WITH EXISTING DATA

6.1 Performance predictions

In the extrapolation of the model test results to full scale conditions, eq. 3b and 4b for the net ice resistance were assumed valid, while the resistance in clear water was based on Murdey's (1980) extrapolation and expressed in the following form

\[
R_{ow} (kN) = 4.41 V + 2.56 V^2 + 0.155 V^3 \quad (V < 6 \text{ m/s}) \quad (10a)
\]

\[
R_{ow} (kN) = 152 + 54 (V-6) + 14.2 (V-6)^2 \quad (V > 6 \text{ m/s}) \quad (10b)
\]

In the full-scale performance predictions, eq. 6 to 9 for \( K_t \) and \( K_q \) in ice and in clear water were used. Because of the large uncertainty on t in level ice, as discussed above, it was decided to use expressions for t...
derived from Murdey's (1980) clear water test results.

At model scale \( t = 0.04 + 0.12 V \) \((V < 1.20 \text{ m/s})\) (11)

At full scale \( t = 0.04 + 0.027 V \) \((V < 5.37 \text{ m/s})\) (12)

Such performance predictions for ice strength of 450 kPa are shown in Figure 4a for the smooth model and in Figure 4b for the roughened model as maximum speed at full power (11,000 kW) versus ice thickness.

6.2 Comparison between predictions and measurements

In its report to the 18th ITTC (ITTC 1987), the Ice Committee presented a reanalysis of available full-scale data from trials with the "Radisson" (Edwards et al. 1981) and the "Franklin" (Michailidis and Murdey 1981). These data are plotted on Figure 4 for comparison with the above performance predictions.

It can be seen that the predictions based on the roughened model resistance and the values of \( K_t \) and \( K_q \) in clear water are in very good agreement with the full scale data, especially for ice thickness up to 0.7 m. This is interpreted as indicating that ice ingestion into the propeller disks was greater at model scale than at full scale. This greater ice effect at model scale is attributed to the facts that the density of model ice is greater than that of real ice which results in more ice entrained into the propellers, and that the model ice floes
entrained into the propellers may be relatively larger than at full scale because of incorrect modeling of ice properties such as elastic modulus or fracture toughness.

7. CONCLUSIONS

From the results of resistance and propulsion tests in ice with models of the same icebreaker at two ice friction factors, the following observations can be made:

- The friction tests with the roughened model showed that $F_T$, the tangential force, was a linear function of normal load $F_N$. The intercept $T_0$ was interpreted as an adhesion force, the exact origin of which remains to be clarified, while the slope was interpreted as the actual friction coefficient, as opposed to the ratio $F_T/F_N$.

- Increasing the model hull roughness led to an increase in ice resistance only in relatively thick ice of low to moderate ice strength. Otherwise, the friction component of the total resistance is too small as compared to the other components to have a significant impact on the total or net ice resistance.

- The thrust coefficient $K_t$ measured with the smooth model was considered incorrect. That with the roughened model in ice was nearly the same as under clear water conditions. The torque coefficient $K_q$ was found to be unaffected by hull roughness and much greater than under clear water conditions. This indicates that ice-propeller interaction had negligible influence on the propeller thrust but increased significantly the propeller torque, at least at model scale.

- Predictions of maximum ship speed at full power versus ice thickness based on roughened model resistance and propeller characteristics in clear water showed excellent agreement with full-scale trials data for ice thickness up to 0.7 m. For thicker ice good comparison was obtained when the propeller characteristics from tests in ice were used in the prediction algorithms. It was concluded that ice effect on propulsion was exaggerated in model tests at relatively high speed in ice of low to medium thickness, but was correctly modeled in thick ice.

These conclusions, if at all valid, apply only for that particular icebreaker over the range of test conditions.
8. REFERENCES


Tatinclaux, J.C. (1984). Model tests in ice of a Canadian Coast Guard R-Class icebreaker. Special Report 84-6, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH.

Tatinclaux, J.C. and Martinson, C. (in press). Model tests in ice of a Canadian Coast Guard R-Class icebreaker - Part II. Special Report, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH.
MATERIALS AND COMPONENTS IN THE ARCTIC
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S-934 02 ERSMARK, SWEDEN

ABSTRACT

The object of this study was to investigate the adhesive shear strength between ice and pure polymers. The experimental work was here concentrated to the adhesiveness of ice on rubber.

A literature survey showed that the usual approach to handling icing problems seemed to be to alter the chemistry of the surface. The dependence on surface roughness and texture was only briefly mentioned.

The experimental work was focused on:
1) Icing on rubbers
2) The dependence of icing on surface roughness/smoothness.

Different rubber vulcanisates containing only polymer and curing agent (peroxide) were tested with regard to wettability and interfacial shear strength. The effect of different grades and amounts of carbon black was also studied. The wettability was determined from contact angles measured on carefully cleaned mirror smooth rubber sheets and expressed as a hydrophilicity number \( h \).

The highly hydrophobic behaviour of different plant surface textures have also been investigated.

1. INTRODUCTION

Icing on structures and mechanical components, in arctic regions, as well as ice build-up on details submerged in water, is a well-known phenomenon. It involves a broad scale, from the annoying adfreeze on wind-screen wipers and car door seals, to more severe cases like air-craft, vessels at sea, antennae and oil drilling rigs.
In the latter cases, the costs can be very high, not to mention the danger for human lives and equipment.

In this study a particular interest has been to investigate the adhesion, or rather the lack of adhesion between ice and different materials. Lack of adhesion is named abhesion.

Low adhesion against ice is not the only criterion for a coating material against icing. Year around use outdoors means that it must be weather resistant, be able to cope with ultra-violet radiation during day around sunshine in the summer and abrasive snow and ice storms during the winter. Furthermore, the material should show two contradictory properties: While one side of the coating should be completely inert, i.e. preferably nothing should attach to it, the other side must show strong adhesion to the surface to be coated.

2. PURPOSE

In this study the work was concentrated on the adhesiveness of ice to rubber. Since wettability is one of the criteria for adhesion, non-wettability will cause abhesion (Brewis and Briggs, 1985). In order to test the validity of this assumption, rubber materials with different polarities as well as materials containing common rubber chemicals have been tested.

3. EXPERIMENTAL

3.1 Contact angle measurement

Wettability has been measured with the aid of a goniometer, with which contact angles for a sessile drop of liquid placed on the actual surface are determined, Figure 1.

Figure 1. Contact angle measurement (Sayward, 1979).
We are probably more interested in the contact angle itself, rather than the surface energy, since we believe that a large contact angle between a drop of water and the substrate leads to air occlusion with lower ice adhesion as a result. Similar thoughts have been expressed earlier (Sayward, 1979) but very little seems to have been reported from studies adopting this approach to the problem.

A poor wettability should, as earlier mentioned, indicate poor interaction between water and substrate, an interaction that remains as the water turns into ice, with a poor adhesive force as a result.

3.2 Wettability

The work of adhesion can be divided into two parts (Ström, 1987): one part due to the dispersive forces $W_a^d$ on the surface and one part due to the non-dispersive part $W_a^n$ which contains all other types of interactions, e.g. acid-base, dipole-dipole, hydrogen bond etc. i.e:

$$W_a = W_a^d + W_a^n$$ for the adhesive work \hspace{1cm} (1)

The work of adhesion can be calculated using the surface tension of the liquid used, $\gamma_l$, together with the contact angle between the liquid and the solid ($\theta$).

$$W_{a,sl} = \gamma_l (\cos \theta + 1)$$ \hspace{1cm} (2)

Further, the following expression for the dispersive and non-dispersive part of the work of adhesion has been derived

$$W_{a,sl}^d = 2 \sqrt{\frac{\gamma_l}{\gamma_s} \gamma_1^d}$$ \hspace{1cm} (3)

$$W_{a,sl}^n = 2 H \gamma_{l}^n$$ \hspace{1cm} (4)

where $H$ is an interaction parameter which measures the hydrophilicity of the surface

$$H = \frac{W_{as,H_2O}^n}{W_{cs,H_2O}^n} = \frac{W_{as'(H_2O)}^n}{2 \gamma_{H_2O}^n}$$

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Equations 2, 3 and 4 combined with equation 1 yield

\[ \gamma_1(\cos \theta + 1) = 2 \sqrt{\gamma_s^d \gamma_1^d} + 2 \mathcal{H} \gamma_1^n \] (5)

The measurement is divided into two parts:

a) Measuring the contact angle using CH\textsubscript{2}I\textsubscript{2} as liquid. This liquid can approximately be regarded as non-polar, which means that \( \mathcal{W}_a,sl = 0 \).

b) Measuring the contact angle with water.

For \( \mathcal{W}_a,sl = 0 \), equation 5 yields:

\[ \gamma_s^d = \frac{\gamma_{CH_2I_2}^1 (\cos \theta' + 1)^2}{4} \] (6)

where \( \theta' \) is the contact angle between the solid and CH\textsubscript{2}I\textsubscript{2}, \( \gamma_1 \) the surface tension and \( \gamma_s^d \) the surface energy for the solid.

Values for the different parts of surface tension for the two test liquids are (Wu, 1982):

\[ \gamma_{CH_2I_2}^1 = 50.7 \text{ mJm}^{-2}, \gamma_{H_2O}^1 = 72.8 \text{ mJm}^{-2}, \gamma_s^d = 22 \text{ mJm}^{-2} \]
\[ \gamma_{H_2O}^n = 50.8 \text{ mJm}^{-2} \]

After simplification equations 5 and 6 together with the above data yields an expression for \( \mathcal{H} \):

\[ \mathcal{H} = k_1 (\cos \theta + 1) - k_2 (\cos \theta' + 1) \]

where \( k_1 = 0.7165 \) \( \theta \) = contact angle for water
\( k_2 = 0.3287 \) \( \theta' \) = contact angle for Methylene iodide

Some attempt to determine surface energies, \( \gamma_s^d \), of different rubber materials using the equation 6 have been made.

3.3 Adhesion test

The adhesion of ice to the different substrate in this investigation was measured by the shear strength of the adhesive bond between ice
and substrate using the shear button test (Andersson, 1988b).

This type of test was chosen among other common test methods (Sayward, 1979) because it is regarded to be independent of specimen size and direction of shear (Brewis and Briggs, 1985). Further the mode of deformation is probably the most common. Materials tested are described in table 1.

Table 1. Materials tested

<table>
<thead>
<tr>
<th>No.</th>
<th>Material</th>
<th>Grade</th>
<th>Phr Trigonox T</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>P 11903 NR</td>
<td>SMR 5CV</td>
<td>2,5</td>
</tr>
<tr>
<td>2</td>
<td>P 11904 SBR</td>
<td>Buna Huls 1500</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>P 11905 BR</td>
<td>Buna CB10</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>P 11906 NBR</td>
<td>Perbunan 1807 + 2,5</td>
<td>Trigonox T</td>
</tr>
<tr>
<td>5</td>
<td>P 11907 NBR</td>
<td>Perbunan 2807 + 2,5</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>P 11908 NBR</td>
<td>Perbunan 3307 + 2,5</td>
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<tr>
<td>7</td>
<td>P 11909 NBR</td>
<td>Perbunan 3807 + 2,5</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>P 11911 EPDM</td>
<td>Vistalon 4608 + 2,5</td>
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</tr>
<tr>
<td>9</td>
<td>P 11914 IR</td>
<td>SKI 3NS</td>
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<td>10</td>
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</tr>
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<td>11</td>
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<td>30 N 220</td>
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<td>12</td>
<td>P 11941 IR</td>
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<td>14</td>
<td>P 11945 IR</td>
<td>P11914</td>
<td>70 N 990</td>
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</table>

Comments

NR Natural rubber
SBR Styrene butadiene rubber
BR Butadiene rubber
NBR Nitrile butadiene rubber. A copolymer of acrylonitrile (ACN) and butadiene, with 18, 28, 33 and 38% ACN content in this investigation.
EPDM Ethylene-propylene terpolymer
IR Isoprene rubber. A synthetic form of natural rubber (NR)
Q Silicone rubber
N990 Sevacarb MT. Medium Thermal Black, with an average particle size of 200-500 nm

Trigonox T is a 95% tertiary butyl-cumyl peroxide used as a vulcanization agent.
4. INFLUENCE OF SURFACE ROUGHNESS - SMOOTHNESS ON WATER CONTACT ANGLE

Earlier studies (Brewis 1972, Sayward 1979, Iyer and Chanekar 1974) has shown that a contact angle greater than 90°, measured on a smooth surface, increases with increased surface roughness.

We have observed very high contact angles measured on leaves of certain plants. A surface with this property will show a silverly shine, when immersed in water. This is named "the gaseous plastron effect" and the effect is believed to be due to a thin layer of air, entrapped between the water and the substrate (Sayward, 1979). The material will resist penetration of a liquid, if the imposed pressure is below a certain entrance pressure (Wake, 1982).

The methods of investigation have been scanning electron microscopy (SEM), contact angle measurements and measurements of the tilt angle at which a drop with a specified volume rolls or slides of the surface (Andersson, 1988a). See fig 2.

5. RESULTS AND DISCUSSION

The results from test series with different materials are shown in fig 3. There is a clear tendency for increasing shear strength with increasing rubber polarity (specimen 4-7).

Adding a reinforcing carbon black like ISAF N220 increases the rubber strength and since the surface energy usually is related to intermolecular forces (Wu, 1982) the surface energy is expected to increase and hence the adhesion to ice. This effect is seen in fig 3, specimen 11 and 12, while the effect is much smaller for a non-reinforcing carbon black, MT N990 specimen 13 and 14.

In figure 4, the adhesive shear strength is plotted versus the hydrophilicity number and the correlation to the adhesive shear strength is reasonably good.

As can be seen in fig 5, there seems to be no correlation between the rubber hardness and the shear strength in this hardness interval. This supports the assumption that the level of adhesion shear strength is more a result of surface energy. This is especially clear for the different grades of NBR.

Fig 6 shows the adhesive shear strength versus calculated dispersive part of the surface energies $\gamma^d_{s}$ for the different compounds. Although the latter values do not all agree with data presented in earlier investigations (Sugita, 1987), the correlation to adhesive shear strength seems to be quite good.
The surface energy for BR, No 3, should be equal to the surface energy for IR, No 9. The great discrepancy found in this test was not expected and cannot readily be explained, but may be due to impurities in the sample or interaction by the liquid.

At the glass transition temperature, $T_g$, polymeric materials are transformed from the rubber state to a more glassy state, with an approximately thousand-fold increase in elastic modulus within a narrow temperature interval. Fig 7 shows the relationship between strength and $T_g$. A discrepancy is apparent in the case of specimen No 12, which contains a high proportion of a reinforcing agent, ISAF N220. This again indicates the influence of surface energy on the adhesive shear strength.

Attempts to find a correlation between the extreme hydrophobicity of a certain surface texture and low ice adhesion have so far failed. When the water transforms into ice, a mechanical keying effect will occur and give rise to adhesive forces. However, as long as the water is in liquid form, only the edges of the drop will interact with the substrate and this would keep the surface dry and perhaps delay the icing process. (Itagaki, 1983).

Preliminary tests on different plants investigated also show that a drop of water placed on a substrate with macroscopic contact angles of approximately $160^\circ$ will adhere to the surface when frozen, though the drop is almost impossible to place on the substrate by specimen preparation.

The work to characterize these surfaces will however be continued.

6. CONCLUSIONS

A correlation between wettability and the adhesive shear strength in the bond between pure rubber compounds and ice is shown. An expected increase in bond strength is observed with increased polymer polarity. The type and amount of carbon black clearly affects the adhesion to ice. The influence of surface energy is higher than the influence of the glass transition temperature, $T_g$. 

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7. REFERENCES


Fig 2. Dimensionless force acting on a sessile drop versus measured contact angle when the drop starts to move on a tilted plane. Surfaces of different leaves examined.

Fig 3. Adhesive shear strength versus materials. Specimen thickness = 5.25 mm. Materials according to table 1. Test temp = -14.5°C.

Fig 4. Adhesive shear strength versus hydrophilicity number. Specimen thickness = 5.25 mm. Numbers according to materials listed in table 1.
Fig 5. Adhesive shear strength versus substrate hardness. Materials according to table 1. Specimen thickness = 5.25 mm.

Fig 6. Adhesive shear strength versus the dispersive part of substrate surface energy, $\gamma^d$. Materials according to table 1. Specimen thickness = 5.25 mm.

Fig 7. Adhesive shear strength versus glass transition temperature. Materials according to table 1. Specimen thickness = 5.25 mm.
CRACKING OF ROOF FELT CAUSED BY AN ICE-COVER

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ABSTRACT

This paper presents a model that simulates the influence of an ice-cover on a flat roof covered by layers of roofing felt. The interaction between the sub-structure of the roof and the ice-cover is demonstrated. Conditions for cracking of the ice-cover are derived and it is shown that in order to resist the local deformations in the vicinity of the crack, the roofing felt must have an ultimate strain capacity of the magnitude 4.0%.

The bonding properties between the ice and the roofing felt have been experimentally investigated and the tests are also described in this paper.

1. BACKGROUND

Some years ago a number of damages were observed on roofs in Sweden with a small slope and covered with a three layered roofing felt. The first signs of damages were cracking of the exterior layers of the roof felt. The cracks did not seem to follow any regular pattern. As often as they crossed the joints in the sub-structure they could run parallel to them. There were indications that the stresses in the felt were due to other reasons than movements in the sub-structure. The damages seemed
moreover to have occurred in roofs built in the years 1960 to 1975. During this period there has been a change in the composition of the outer layer of the roofing felt. The older rags or textile based felt has been substituted by a mineral fibre based felt. By this substitution of an organic material with an inorganic one, a better durability but in some respects less good mechanical properties have been obtained. One decisive mechanical property is constituted by the ultimate strain capacity and it amounts to about 4\% for the organic felt whereas it only amounts to about 2\% for the inorganic felt.

The hypothesis of the authors is that an expanding ice-cover at one or more occasions is the reason to the increasing number of damages. According to a failure mechanism described below, one has to use a roofing felt with an ultimate strain capacity of the order of 3 to 4\% in order to avoid that it will be teared apart by a cracking ice-cover.

A first condition for damages of this kind to occur is thus that the roof has such a shape that an ice-cover can be generated. The configuration of the roof must thus admit small water ponds or that water from a melting snow-cover is retained to the next freezing period. It is thus roofs with a small slope that are exposed to damages of this kind and this is, according to the opinion of the authors, independent of the dewatering system if it thus is through interior or exterior drainage. It is also very difficult to build roofs with small slopes so that the risk of ponded water with a smaller height than about 4 or 5 cm can be completely avoided.

It must thus be concluded that by the climate conditions which are prevalent in a large part of the Nordic countries, the roofing felt on roofs with a small slope must resist the influence of an ice-cover of a thickness of 4 or 5 cm.

It is likely that the greatest risk of damaging the felt exists when an ice-cover at a sudden drop of temperature contracts and eventually cracks. When the ice is cracked, tensile forces in the ice are transferred to the felt and the risk of tearing is obvious. A theoretical model for the interaction between ice-cover, roofing felt and roof below the felt is presented in the following. Some tests which were necessary in order to determine the magnitude of the bond between the felt and the ice-cover are also described.
2. NECESSARY CONDITIONS FOR THE CRACKING OF AN ICE-COVER

An uncracked continuous ice-cover is assumed to have been frozen to top of a roofing felt which is glued to an insulating layer according to figure 1. It is assumed that the insulating layer admits some shear deformations. It is moreover assumed that the insulating layer is glued to a rigid structural element. The ice-cover is extended a distance of 1 in the main direction and it has a mean thickness of $h_i$.

![Figure 1. An ice-cover with a continuous extension = 1 and thickness $h_i$](image)

At a sudden drop $\theta$ of the temperature, a contraction of the ice-cover is obtained and resisting forces in the sublayers are mobilized due to shear deformations. In a certain section defined by the coordinate $x$ (the origin located to the middle of the ice-cover) a displacement $\varphi$ of the ice-cover is obtained. This displacement is assumed to be associated with a shear stress $\tau$ in the insulating sublayer according to figure 2.

![Figure 2. Shear deformations in the sublayer](image)

The constitutive relation between the shear stress $\tau$ and the displacement $\varphi$ is assumed in accordance with eq. (1):

$$\tau = k_s \cdot \varphi$$

(1)

where $k_s$ thus constitutes the modulus of displacement for the insulating sublayer. With a given thickness $t$ of this layer the modulus of displacement $k_s$ can be related to the shear modulus $G_s$ of the sublayer material.
On account of the shear stresses in the sublayer, the tensile force $N$ in the ice-cover is changed from section to section according to figure 3.

![Figure 3. Change in magnitude of the tensile force $N$ due to shear stresses in the sublayer](image)

The equilibrium condition claims that:

$$\tau \, dx + dN = 0$$

or

$$\tau = -N'$$  \hspace{1cm} (3)

In this stage of interaction between the ice-cover and the sublayer, the roofing felt is assumed to follow the movements of the ice-cover with very small imposed deformations. The displacement $\varphi$ between the ice-cover and the rigid structure below the insulating layer can, provided that no displacements occur in the middle of the ice-cover, be formulated as:

$$\varphi = \alpha_i \cdot \theta \cdot x - \int_{0}^{x} \frac{N}{E_i \cdot h_i} \, dx$$  \hspace{1cm} (4)

where $\alpha_i$ is the temperature expansion coefficient of ice and $E_i$ the modulus of elasticity for ice.

The first term in eq. (4) accounts for the free temperature expansion and the second term accounts for the influence of the resisting forces from the sublayer. By elimination of $\varphi$ and $\tau$ from eq. (1), (3) and (4), the governing differential equation is obtained on the form:

$$N'' - \kappa^2 N = - \alpha_i \cdot \theta \cdot k_s$$  \hspace{1cm} (5)

where $\kappa^2 = \frac{k_s}{h_i \cdot E_i}$  \hspace{1cm} (6)

The general solution to eq. (5) is:
\[ N = A \sinh \kappa x + B \cosh \kappa x + \alpha_i \cdot \theta \cdot h_i \cdot E_i \]  \hspace{1cm} (7)

With the boundary conditions:

\[ N = 0 \text{ for } x = 0.51 \]

and \[ N' = 0 \text{ for } x = 0 \]

the special solution for this actual case can be written as:

\[ N = \alpha_i \cdot \theta \cdot h_i \cdot E_i \left(1 - \frac{\cosh \kappa x}{\cosh \kappa 0.51}\right) \] \hspace{1cm} (8)

If the force \( N \) in the ice-cover corresponds to stresses close to the tensile strength of the ice, there is a risk of cracking of the ice-cover. It is possible to determine theoretically the least extension \( l_{\text{min}} \) of the ice-cover in order to get one crack in the middle of the ice-cover. With the tensile strength = \( \sigma_i \) one gets:

\[ l_{\text{min}} = \frac{2}{\kappa} \arccosh \frac{\alpha_i \cdot \theta \cdot E_i}{\alpha_i \cdot \theta \cdot E_i - \sigma_i} \] \hspace{1cm} (9)

For reasonable variations of the pertinent parameters the value of \( l_{\text{min}} \) varies according to figure 4.

![Figure 4. The least extension \( l_{\text{min}} \) of an ice-cover in order to get one crack (\( \alpha_i = 5 \cdot 10^{-5}, \ E_i = 1.0 \ \text{GPa} \))](image-url)
The investigation reported in [1] and [2] have been the basis for the choice of values of the modulus of displacement $k_s$ and material parameters of the ice-cover. A temperature drop of $\theta = 10^\circ C$, which has been chosen in the diagram of figure 4, can be obtained during a shorter time than a day in most places of the Scandinavian countries.

When cracking occurs in the ice-cover and it is separated into two parts which are displaced from each other, the roofing felt is exposed to great stresses and strains. The felt can resist harmful damages either through stress capacity or through strain capacity. In other words, if the strength of the felt is greater than that of the ice, or if the strain capacity is with some margin greater than the obtained strain in the middle of the ice-crack, there will be no tearing of the roofing felt.

In the theoretical model presented below an estimation is made of the strains obtained in the felt in the middle of an ice-crack. It is assumed that the strength of the felt is less than that of the ice-cover. The magnitude of this strain is dependent upon the bond stresses developed between the felt and the ice. To get an estimate of the bond stresses, some tests have been performed and they are described in the last chapter.

3. STRAINS IN THE ROOFING FELT IN THE MIDDLE OF AN ICE-CRACK

In the following analysis it is assumed that the ice-cover is frozen to the roofing felt all over the contact surface and the crack is assumed to divide the ice-cover in two equal parts. Each part of the ice-cover is assumed to get a new displacement centre at a distance $l_s$ from the crack according to figure 5. With new coordinates located to the new displacement centre, the same governing equation and the same general solution as in the previous chapter is obtained:

$$N = A \sinh \kappa x + B \cosh \kappa x + a_1 \cdot \theta \cdot h_i \cdot E_i$$  \hspace{1cm} (10)

Eq. (10) is valid for the behaviour at each side of the chosen origin but the constants $A$ and $B$ will be different due to different boundary conditions. At $x = l_s$ the force $N$ is supposed to be equal to $N_p$ corresponding to the maximum stress capacity of the felt but attained at a strain less than the ultimate strain capacity. At $x = -(0.5l - l_s)$ the force $N$ is equal to zero. At
x = 0 the boundary condition will be \( N' = 0 \) in agreement with the fact that the origin is localized to the displacement centre.

![Diagram of crack and displacement center](image)

Figure 5. The ice-cover according to figure 1 is divided into two parts by the crack and each part has got a new displacement centre at a distance \( l_s \) from the crack.

The force \( N \) in the ice-cover can be deduced to:

\[
N = N_p \frac{\cosh \alpha x}{\cosh \alpha l_s} + \alpha_i \cdot \theta \cdot h_i \cdot E_i (1 - \frac{\cosh \alpha x}{\cosh \alpha l_s}) \tag{11}
\]

for \( x \geq 0 \)

and to

\[
N = a_i \cdot \theta \cdot h_i \cdot E_i (1 - \frac{\cosh \alpha x}{\cosh \alpha (0.5l - l_s)}) \tag{12}
\]

for \( x \leq 0 \).

The distance \( l_s \) can be determined by putting \( N \) according to eq. (11) equal to eq. (12) for \( x = 0 \) which condition can be formulated as:

\[
N_p = a_i \cdot \theta \cdot h_i \cdot E_i (1 - \frac{\cosh \alpha l_s}{\cosh \alpha (0.5l - l_s)}) \tag{13}
\]

Eq. (13) has been solved for two different values of \( N_p \) namely \( N_p = 10 \) kN/m and \( N_p = 15 \) kN/m and for two different values of the characteristic length \( l \) of the ice-cover namely \( l = 6.0 \) m and \( l = 8.0 \) m. The results of these calculations are presented in figure 6. The thickness of the ice-cover has been chosen to \( h_i = 0.05 \) m which means that the ice with an assumed tensile strength of \( \sigma_i = 0.40 \) MPa can cause fracture of the roofing felt when \( N_p \leq 20 \) kN/m in cases when the strain capacity is too low.

When the dilatation length \( l_s \) is known, the crack width \( \Delta \) can be calculated as twice the displacement for \( x = l_s \) with the
origin located according to figure 5. From eq. (1), (3) and (11) we get:

$$\Delta = 2\varphi = -\frac{2N'}{k_s} = 2 \left[ a_i \cdot \theta - \frac{N_p}{h_i E_i} \right] \frac{tgh \cdot l_s}{\kappa} \quad (14)$$

The variation of $\Delta$ has been illustrated in figure 7 for the same values of $N_p$ and $l$ as in figure 6.

**Figure 6.** The dilatation length $l_s$ function of the stiffness $k_s$ of the insulating layer for two different values of the felt strength $N_p$ and the original extension $l$ of the ice-cover.

**Figure 7.** The crack width $\Delta$ as a function of the stiffness $k_s$ of the insulating layer.
It is obvious from figure 7 that the crack width $\Delta$ is rather insensitive to the stiffness of the insulating layer within relatively great intervals.

In order to estimate the required ultimate strain capacity for a roofing felt, it can be reasonable to assume a strength $N_p = 15 \text{ kN/m}$ and an original extension of the ice-cover of $l = 8.0 \text{ m}$. The maximum crack width for this choice of parameters amounts to $\Delta = 0.40 \text{ mm}$ according to figure 7. The force transfer and the related strain distribution in the felt in the vicinity of the crack is shown in figure 8. The force in the felt thus increases from zero to the maximum capacity $N_p$ in a length $l_t$ that can be named the transfer length.

![Diagram](image)

**Figure 8.** The force transfer between ice and felt and the strain distribution in the felt in the vicinity of the ice crack

The transfer length is in this study estimated from the bond tests which have been especially performed for this purpose. These tests are shortly described in the next chapter. It can be evaluated from these tests that the mean value of the ultimate bond stress amounts to $r_b = 0.75 \text{ MPa}$. The strength capacity $N_p = 15 \text{ kN/m}$ thus corresponds to a transfer length:

$$l_t = \frac{N_p}{r_b} = \frac{0.015}{0.75} = 0.020 \text{ m} = 20 \text{ mm}$$

It has not been possible to determine the exact strain distribution in the roofing felt but it is natural to assume some deviation from a linear relationship. In order to make an estimation of the required ultimate limit capacity $\varepsilon_u$, it is in one approach assumed a second order parabolic relation and in a second approach a third order parabolic relation. The mean strain
\( \varepsilon_m \) on the transfer length can then be written as:

\[
\varepsilon_m = \alpha \cdot \varepsilon_u
\]

where \( \varepsilon_u \) thus signifies the maximum strain in the middle of the crack. The value of \( \alpha \) varies between \( \alpha = 1/3 \) and \( \alpha = 1/4 \) for the different assumed strain distributions.

The strain compatibility can now be formulated as:

\[
\Delta = (\Delta + 2 \alpha b \cdot \varepsilon_u)
\]

and this results in an expression for \( \varepsilon_u \):

\[
\varepsilon_u = \frac{\Delta}{\Delta + 2 \alpha b}
\]

The two values 1/3 and 1/4 of \( \alpha \) thus corresponds to:

\[
\varepsilon_u = 2.9\% \text{ and } \varepsilon_u = 3.8\%
\]

respectively.

For a roofing felt with an ultimate strength not less than 15 kN/m it seems reasonable to require an ultimate strain capacity \( \varepsilon_u \geq 4\% \).

4. THE BOND STRENGTH BETWEEN A ROOFING FELT AND AN ICE-COVER FROZEN FAST TO THE FELT

The bond test was designed according to figure 9 from which can be seen that a roofing felt has been glued to each side of a steel sheet which thereafter has been frozen to ice logs. The freezing operation has occurred in a freezing chamber at \(-10^\circ C\) and the test has been performed at the same temperature. The displacement between sheet and ice has been continuously registered for an increasing load \( P \) on the sheet according to figure 9.

The measured displacement was very small and sudden jumps in the force-displacement curve are probably due to local bond failures whereby the stresses in the contact surface are redistributed. In almost all tests several local maxima were obtained before ultimate failure. The highest and the lowest of these maxima are given in table 1. The highest value was always obtained first. From the table it can be seen that the variations are within reasonable limits and the experimental study can be
assumed to give a good estimation of the bond strength.

Figure 9. The design of the bond test for the verification of the bond strength between ice and roofing felt

Table 1. The bond strength between a roofing felt and an ice-cover frozen fast to it

<table>
<thead>
<tr>
<th>Test no.</th>
<th>Max $f_b$ [MPa]</th>
<th>Min $f_b$ [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.76</td>
<td>0.61</td>
</tr>
<tr>
<td>2</td>
<td>0.88</td>
<td>0.72</td>
</tr>
<tr>
<td>3</td>
<td>0.79</td>
<td>0.76</td>
</tr>
<tr>
<td>4</td>
<td>0.75</td>
<td>0.49</td>
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<tr>
<td>5</td>
<td>0.57</td>
<td>0.40</td>
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<tr>
<td>6</td>
<td>0.81</td>
<td>0.70</td>
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<td>7</td>
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<td>8</td>
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<td>-</td>
<td>-</td>
</tr>
<tr>
<td>10</td>
<td>0.82</td>
<td>0.78</td>
</tr>
</tbody>
</table>

Mean 0.75 0.62
5. REFERENCES


BEHAVIOUR OF CONCRETE AT LOW TEMPERATURES

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ABSTRACT

Research at Luleå University of Technology have been focused on fracture mechanics properties of hardened concrete at low temperatures.

The paper presents an experimental investigation of the fracture energy and the fatigue strength of unreinforced concrete.

1. TEST SPECIMENS AND TEST PROCEDURE

Unreinforced concrete beams and cubes have been tested, see Fig. 1. Five concrete qualities with aggregates of granite, C25 and C40, Brusdal and Krekula (1987), C40A, Andersson (1989), C40B, Ohlsson (1989), C100, Wallgren (1987) and two concrete qualities with lightweight aggregates, LC45A, Solaas and Rindal (1987), LC45B, Alvestad and Jørgensen (1987) were used, Table 1.

The beams and cubes were cast in steel moulds. After the casting the specimens were covered with plastic film and kept wet. The specimens were removed from the moulds after three days and were then cured in water. At the end of the curing time, notches were sawn in the beams.

Concrete qualities C25 and C40, Brusdal and Krekula (1987), were stored in +20°C in 3-4 days before they were tested or put into the climate chamber. The other series were taken from a water basin and were kept sealed in plastic wrappings in the climate room up to testing.

The tests were carried out in three point bending according to the tentative RILEM recommendations, RILEM TC 50-FMC (1985). The test rigs were

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placed in a climate chamber, see Fig. 2. Series C40A,B and LC45B were tested with a 130 kN closed-loop servohydraulic actuator and the other series in an ordinary 200 kN hydraulic press.

![Beamtype B and Beamtype A]

Figure 1. Test specimen

Table 1. Concrete mixes

<table>
<thead>
<tr>
<th>Concrete Reference Number</th>
<th>Beam Type</th>
<th>Cement</th>
<th>w/(c+s) (kg/m³)</th>
<th>s/c</th>
<th>f_{oc} (MPa)</th>
<th>f_{ct} (MPa)</th>
<th>Age at testing (days)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>C25</td>
<td>B</td>
<td>248</td>
<td>0.60</td>
<td>0</td>
<td>30.3</td>
<td></td>
<td>28</td>
<td></td>
</tr>
<tr>
<td>C40</td>
<td>B</td>
<td>378</td>
<td>0.49</td>
<td>0</td>
<td>43.5</td>
<td></td>
<td>28</td>
<td></td>
</tr>
<tr>
<td>C40A</td>
<td>A</td>
<td>372</td>
<td>0.48</td>
<td>0</td>
<td>52.7</td>
<td>4.1</td>
<td>39-42</td>
<td></td>
</tr>
<tr>
<td>C40B</td>
<td>A</td>
<td>372</td>
<td>0.48</td>
<td>0</td>
<td>64.0</td>
<td>3.8</td>
<td>91</td>
<td></td>
</tr>
<tr>
<td>LC45A</td>
<td>A</td>
<td>375</td>
<td>0.35</td>
<td>0.10</td>
<td>59.7</td>
<td>4.9</td>
<td>44-46</td>
<td>(1)</td>
</tr>
<tr>
<td>LC45B</td>
<td>A</td>
<td>375</td>
<td>0.42</td>
<td>0.10</td>
<td>65.1</td>
<td>4.0</td>
<td>110</td>
<td>(2)</td>
</tr>
<tr>
<td>C100</td>
<td>A</td>
<td>470</td>
<td>0.31</td>
<td>0.15</td>
<td>96.0</td>
<td>7.1</td>
<td>49</td>
<td>(3)</td>
</tr>
</tbody>
</table>

Notes: w = water, c = cement, s = silica [kg/m³]
(1) Quick hardening cement
(2) Leca 4-8 mm, 300 kg/m³. Leca 8-12 mm, 300 kg/m³.
   Plasticizer 3.75 kg/m³ (Rescon P).
(3) Plasticizer 10.0 kg/m³.
2. EXPERIMENTAL RESULTS

Influence Of Low Temperatures On The Fracture Energy

The Fracture Energy $G_{FE}$ has been determined in a stable three point bend test for the concrete types listed in Table 1. The result is presented as the increase in absolute terms in Figure 3a, together with test results obtained by Elices et al. (1987) in three-point bending. As can be seen, the experimental fracture energy $G_{FE}$ increases when the temperature decreases, and the increase can be significant even for a moderate temperature decrease.

On the whole, the largest increase was found for the concrete types C25, C40 and C40A,B, with granite aggregates, Portland cement and air-entrainments but no addition of silica fume.

The concrete types C25 and C40 were not completely water-saturated at the time of testing, but had been stored at room temperature 3-4 days before they were cooled to $-35\,^\circ\text{C}$, which partly may explain the smaller increase of $G_{FE}$ compared to C40A,B. The specimen size was also different to all the other tested concrete types, and it is likely that there is a size-effect similar to the results obtained by Elices et al. (1987).
The normalweight high strength CL00 and lightweight high strength LC45A, B concrete types, which contained silica fume, showed a considerably smaller increase of $G_F$ compared to the ordinary types. What is remarkable is that the magnitude of the increase is approximately the same for both types. This suggests that the mechanical properties such as $f_C$ and $f_t$, the type of aggregate, and the amount of cement, is of inferior significance for the increase of $G_F$. Instead it seems to be the degree of porosity and the moisture content in the pores, that governs the increase of $G_F$ at low temperatures.

Influence of Thermal Cycles

The resistance of $G_F$ against freezing and thawing have been investigated for the lightweight high strength concrete LC45B. The test set-up and the specimen size was identical to the tests described above. The temperature cycles employed had a duration of 24 hours and shifted stepwise between 18 and $-26^\circ$C in 12 hours intervals. However, the actual temperature during the cycles measured on the surface of the beams varied between 6 and $-12^\circ$C. The results of the freeze-thaw tests are normalized with respect to the initial value and shown in Figure 3b. Each point represents the mean value of at least three beam tests.

The durability, usually expressed as a change in some mechanical or physical property, in general deteriorates with the number of thermal cycles. The decline is furthermore proportional to the moisture content in the concrete. However, these tests have revealed a somewhat unexpected result, namely that the durability as measured by the fracture energy $G_F$ could improve in the course of the first thermal cycles. This behaviour was not noticed for the flexural strength. The rise of $G_{FE}$ is observed approximately to the 7th cycle, thereafter it starts to decline but it retains a value higher than the initial up to about the 18th cycle before an actual degradation can be noticed. From about the 14th cycle and forward it seems to be a parallel dependence between $G_F$ and $f_{flex}$. Possible sources for the increase of $G_{FE}$ are discussed later in section 4.
Figure 3. (a) Increase of the fracture energy versus temperature
(b) Fracture energy and flexural strength versus thermal cycles
Cyclic tests were performed on beam type A, concrete type C40A,B. The beams were subjected to saw-tooth formed loadcycles with a frequency of 1/15 Hz and a minimum load, $P_{\text{min}}$ of 100 N. The load level $P_{\text{max}}/P_{\text{o}}$ is the ratio between the upper load in a cyclic test and the peak load in corresponding monotonic tests. The test results are shown in Table 2, Fig. 4a and b. The cyclic tests in $-24^\circ$C indicate that concrete with a high moisture content can sustain cyclic loading at load levels high above the peak load in $+20^\circ$C. Also the relative fatigue strength seems to increase in low temperatures.

Table 2. Cyclic tests

<table>
<thead>
<tr>
<th>Test No</th>
<th>$T = -24^\circ$C</th>
<th>$T = +20^\circ$C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Concrete type</td>
<td>$P_{\text{max}}$ (N)</td>
</tr>
<tr>
<td>1</td>
<td>C40A</td>
<td>1412</td>
</tr>
<tr>
<td>2</td>
<td>&quot;</td>
<td>1412</td>
</tr>
<tr>
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<td>1412</td>
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<td>6</td>
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</tr>
<tr>
<td>12</td>
<td>&quot;</td>
<td>1628</td>
</tr>
<tr>
<td>13</td>
<td>C40B</td>
<td>1618</td>
</tr>
<tr>
<td>14</td>
<td>&quot;</td>
<td>1618</td>
</tr>
<tr>
<td>15</td>
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<tr>
<td>19</td>
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</tr>
</tbody>
</table>
Figure 4. Cyclic tests. Load level versus number of cycles at: (a) +20°C, (b) -24°C.
Influence of low temperatures on the brittleness

The brittleness of an object depends on the material properties and the size. The brittleness number, $B$, is dimensionless and can be expressed as

$$ B = \frac{L f^2_t}{E G_F} $$

where $L =$ size of the object (m), $f^t_t =$ tensile strength (MPa), $E =$ modulus of elasticity (GPa), $G_F =$ fracture energy (N/m$^2$)

A high brittleness number means that an object behaves brittle.

If we compare the material parameters for concrete type C40A at $+20^\circ$C and $-24^\circ$C we see that the tensile (splitting) strength increases 46 %, the fracture energy increases 110 % and the modulus of elasticity increases 79 %. Thus the brittleness number decreases to 57 % of the value obtained in $+20^\circ$C. The tested beam therefore behaves less brittle at $-24^\circ$C.

3. PHENOMENA OF FREEZING

The mechanical and physical properties of concrete at low temperatures may differ considerably from those more familiar at ambient temperatures. The explanation to this behaviour is to be sought in the microscopic structure of the material since it influences the macroscopic properties. Ordinary concrete may be regarded as a two-phase composite material consisting of natural aggregates and cement paste. Hardened cement paste is in turn a highly multi-component system consisting of solid gel particles, water, air, and at sub zero temperatures also ice. Natural aggregates is normally non-porous while cement paste in comparison is a material of high porosity and of great specific surface, and thus may contain a considerable amount of evaporable water.

The mechanism of freezing and frost damage have been investigated by a number of researchers, and the subject is covered in several literature studies, for example Setzer (1977), Wiedemann (1982) and van der Veen (1987). Factors of fundamental importance is the moisture content in the concrete and the temperature.

The mechanism of freezing of water in the porous system of hardened concrete differs significantly from the freezing of bulk water. In cement paste the freezing point is depressed to lower temperatures. This phenomenon can be explained by thermodynamics and is mainly a function of the pore size, Setzer (1977). The smaller the voids are, the lower the freezing
point will be. This implies that there exist no specific freezing point, but instead a transition zone where the change of phase gradually takes place over a certain temperature range, and where ice, non-frozen water and vapour will coexist.

The freezing of water is accompanied by a volume increase of 9 %, which induces a volume change of the concrete as illustrated in Figure 5. The magnitude of the expansion in the transition range is governed by the moisture content. It is greatest for water-saturated concrete, while concrete stored a long time at indoor climate exhibits an almost linear thermal deformation similar to steel. Furthermore, water-saturated concrete upon reheating attains irreversible deformations, which indicates a permanent structural damage of the cement paste. High hydraulic pressure generated by the volume expansion of ice is in general thought to promote micro-cracking, but it may also have a positive effect in that it "prestresses" the cement paste and the aggregate/paste interface, and thus obstructing crack initiation and propagation.

![Thermal strains versus temperature of prestressing steel, partially dry and water-saturated concrete. From FIP (1982)](image)

When water turns into ice, the microscopic structure changes radically and this affects the macroscopic behaviour. The mechanical and physical properties are influenced as a consequence in one way or another, and the change can be remarkable. For instance, the compressive strength may be
three-doubled, the tensile splitting strength doubled, and the fracture energy, as shown in Figure 3a, three-doubled at the most. Physical properties such as permeability, thermal conductivity and thermal diffusivity increase, while the specific heat capacity decreases with the reduction of temperature. The magnitude of change is mainly related to the moisture content at the time of cooling.

The increase in strength is in the literature attributed to several bieffects of the moisture content, of which the most common are:

- The ice within the pores forms a solid mesh of veins which completely permeates the concrete and contribute to the load carrying capacity.

- Because the ice fills the pores and pre-existing microcracks, they will not act as stress-raisers and thereby abating the process of micro-cracking.

The enhanced homogeneity of the concrete may be quantified by the stiffness ratio of the aggregates and the cement paste. At room temperature, the Young's modulus of aggregate and cement paste is approximately 70 and 20 GPa, respectively. At cryogenic temperatures, Zech and Setzer (1988) have determined the increase of the dynamic Young's modulus of hardened water-saturated cement paste with a porosity of 40% to be about 40% at -60 and about 80% at -160°C, compared to the value at room temperature of 19.3 GPa. A relative increase of the same magnitude for the Young's modulus of the aggregates is not known.

4. DISCUSSION AND CONCLUSIONS

The influence of low temperatures on the fracture energy follows that of all other mechanical properties, namely that the increase is proportional to the decrease in temperature and to the moisture content. The magnitude of the increase, as demonstrated by Elices et al. (1987), is of the same order as for the compressive strength. However, it is so far not possible to tell whether the fracture energy has a local maximum in common to the tensile splitting strength, or if it increases monotonically down to -170°C similar to the compressive strength. Future tests in the temperature range between -40 and -170°C may give an answer to that.

The initial increase of $G_{FE}$ during the first freeze-thaw cycles, is of a temporary nature, and probably a product of several interlinked effects. The presence of silica fume combined with a low w/c+s-ratio is probably
the most reasonable explanation. It is well-known for ordinary concrete that a w/c-ratio < 0.4 theoretically do not yield any capillary pores in the cement matrix. For lower w/c-ratios the amount of water is insufficient to achieve a complete hydration, which will result in inclusions of unaffected cement. The unhydrated cement may then be looked upon as an inherent reserve which can be utilized if it comes in contact with water. This may happen when the concrete is subjected to thermal cycles. It can be imagined that the microcracks formed during the thermal cycles penetrates cells of unhydrated cement and by that giving access to water, resulting in a resumed hydration in the thawing regime of the cycles. This process is believed to continue for as long as there is unhydrated cement available. When this resource is exhausted, there is nothing that counteracts the deterioration due to the freezing of the pore water. This effect is often referred to as autogeneous healing, and it may explain the increase of $G_{FE}$ in the course of the first cycles.

The cyclic tests indicate that concrete with a high water content increases its relative fatigue strength when subjected to low temperatures. Several factors can contribute to this. One explanation is that large parts of the pore system in a frozen concrete is filled with ice. The cement paste becomes more dense and the concrete more homogenous. In such a concrete fewer stress concentrations occurs and the cracking will therefore not be so extensive during fatigue loading. Another explanation is that the amount of consumed energy during one load cycle is larger for the frozen concrete because of partial healing of the cracks during the unloading cycles when local compressive stresses occurs. One third explanation has to do with the different thermal expansions for the concrete paste and aggregates. When the temperature is lowered the cement paste will expand due to the freezing of free water in the paste. This expansion will "prestress" the interface between aggregates and cement paste and thus prevent crack formation.

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Problems of design and service of machinery and structures under cold climate conditions are considered. An analysis of failures of machinery parts and structure elements used at low temperatures is fulfilled. New criteria to assess the behaviour of materials (including polymers) under those conditions are suggested together with the ways enabling the machinery and structure serviceability to be improved. A special attention is paid to the problems of low-alloy steel weldability and ageing of polymer materials.

1. GENERAL

Serviceability and reliability of machinery and structures used outdoors in the cold climate zone depend, mainly, on specific features of their use under given climate conditions both from a position of comfort for operator and from that of conformity of structure materials, design and technology to specific service conditions (Fig.1).

From analysis of machinery serviceability and fracture of parts and welded joints at low temperatures one can draw a conclusion about a certain pattern of low temperature failures of the main kinds of machinery and structures[7,8,10,12,13].

Failure rate of parts and units of trucks, tractors, bulldozers in winter increases 4–6 times in comparison with summer period. Capacity of common machinery at a monthly average temperature $-35\ldots-40^\circ\text{C}$ falls by 40% and operating longevity in the zone of
annual average subzero temperature reduces 1.5 times. The monthly average capacity per bulldozer in winter falls 2.7-7 times as against in summer period; 75% of the total number of registered failures of welded basic units and parts of excavating machines occur in winter time (October-March). Brittle fracture of welded joints at low temperatures are caused by uprated dynamic and cyclic load of working parts of excavating machines.

Fig. 1 Main trends of... where: 1-improvement of base material quality; 2-modification of calculation methods for design and styling of machines and structures for polar regions; 3-optimization of fabrication technology; 4-improvement of maintenance conditions at low temperatures; 5-methods of improvement of steel and alloy cold resistance and weldability; 6-development and choice of reasonable criteria of cold resistance assessment; 7-optimization of welding procedure, development and selection of filler materials; 8-high quality of inspection, maintenance, erection workmanship, overhaul and current repair; 9-development of cold resistant polymer, composite, metal-polymer materials; 10-consideration of the loading nature (static, dynamic, cyclic, casual etc.) at low temperatures; 11-optimization of iron and steel casting technolo-
gy, development and selection of composition, modification methods; 12-modification of damping systems; 13-development of cold resistant rubber parts; 14-consideration of stress-strain state at low temperatures; 15-optimization of technology in fabricating polymer, composite, metal-polymer and rubber articles; 16-better education and training of operators and servicing people; 17-use of special fuels and lubricants; 18-application of auxiliary treatments (thermal, thermomechanical, by plasma, explosion etc.); 19-improvement of road pavement and profile; 20-improvement of production technology (in mining, earth moving etc.) at low temperatures.

Fatigue damages accumulate in the structure elements of dredges during a long-term operation under repeated loads. The average annual amount of fracture of dredge piles and scooping ladders depends considerably on in service time. A relative frequency of brittle fractures of welded parts of dredge basic units increases abruptly as the in-service temperature goes down below -30°C.

Mischoice of base and welding materials and welding practice predominates among brittle fracture causes when welding at low temperatures. As a result of non-optimum practice and mischoiced materials, sites of higher susceptibility to brittleness and cold fatigue cracks are formed (Fig. 2). In low temperature material science, metallurgical methods of strength, cold resistance and weldability control, for example, of steel rolled products are of great importance (Fig. 3).

During development of cold resistant antifriction polymeric materials, a very promising trend is the use of ultradispersive high-activity fillers, which enables one to change deliberately properties of compositions acting, first of all, on their intermolecular structure. So, fluoroplastic composites with 2...5% of fillers having dispersity of 0.1-1 μm keep up elasticity and strength, so necessary for use in seals at the matrix level, and have a 10...100-fold improved wear resistance and a substantial decrease in viscoelasticity.

Improvement of calculation methods is one of the fundamental trends in eliminating low temperature failures. We have made an attempt to carry out an experimental verification of the strength criteria introduced by Mises, Huber, Tresca and others for the case when there are stress and strain concentrators.
Fig. 2. Distribution of brittle fracture in welds according to:
(a) levels of effective nominal stresses, and (b) breakdown causes.
(a) 1-pipelines, 2-building structures, 3-excavating machines,
4-bulldozers;
(b) I-ship hulls, II-pipelines, III-building structures, IV-bulldozers,
V-excavating machines; I-materials and welding procedure
contribution to weld brittle fracture; 2, 3-cold and fatigue
cracks, respectively; 4-design shortcomings; 5-non-acceptable welding defects.

Fig. 3. Main ways to master strength, cold resistance and weldability of plate rolled steel:
I- 0.2%C, 1.3%Mn—normalization, upgrading (quenching+tempering);
II- 0.2%C, 1.3%Mn, Nb, V, Mo, Ni, Si, Cr, Cu;
III: a- microalloying + controlled rolling; 0.06%C, 1.8%Mn, 0.3...0.01% (Nb, V, Mo, Cr, Cu, Ni);
b- 0.1%C, 1.5%Mn, 0.3...0.01% (Nb, V); IV:
a- steel making procedure, special metallurgy; low-alloyed steels
hardened by carbonitrides (b); V- alloyed by Cr, Ni, Mn (4...9%).
2. EXPERIMENTS AND CALCULATIONS

In our Institute techniques of local yield determination were developed on the basis of the moire method and holographic interferometry[1,2,4,9]. New experimental opportunities showed that the non-uniformity leads to a substantial error in determination of limiting loads.

By a "local yield strength" we mean a stress of the material flow at the point of structure element with a non-uniform distribution of stresses, for example, on the concentrator contour. It was established that the beginning of local yielding in zones of stress concentrators does not agree with a level calculated using traditional strength criteria, in particular, the Mises-Huber-Hencky criterion. The difference between the experimental stress value of local material plastic flow $\sigma^*_T$ and the calculated one increases when the level of non-uniformity of stress distribution rises. Stress gradients $G$ are responsible for the increase of local material yielding. According to the non-uniformity level, stresses of local plastic flow are defined as follows:

$$\sigma^*_T = \sigma_T \left(1 + \sqrt{\frac{G_i}{L_0}}\right)$$

(1)

where $G_i$ - stress intensity gradient; $\sigma_i$ - stress intensity; $L_0$ - constant. This relationship agrees rather well with experimental results given in literature (Fig. 4).

Fig. 4 Relationships of local yielding stresses vs. stress intensity factor for tensile flat specimens from alloys BCr3Cn5(1), 19AT(2,3) and B95(4). 1, 2, 4 - holography; 3 - moire method; solid line - $\sigma^*_T = \sigma_T[1+\gamma(\sigma_0-1)]$
The derived relationship offers quite a new opportunity for estimating local yield stresses near the concentrators.

Analysis of structure carrying capacity at low temperatures is necessary for evaluating the structure resistance to brittle fracture, as well as for a quantitative determination of changes in service life and probability of failing under new conditions.

Method of impact strength estimate in a wide range of temperatures is one of the most classical approaches in material cold resistance assessment. An important advantage of the method is its exceptional simplicity and ease in handling. But this method offers only a relative estimate of material cold resistance. The prediction of material behaviour in structures using these data is almost always incorrect.

In our Institute were obtained the data on characteristics of crack resistance as applied to steels alloyed by vanadium, niobium and molybdenum promising for pipeline construction, as well as to low-alloyed steels of medium strength. Crack resistance data were estimated according to different criteria of fracture mechanics in a wide temperature range. The applicability range of force, energy and strain criteria was also determined. The use of crack resistance characteristics for prediction of structure behaviour during operation is an important practical task.

The Institute has a testing site for full-scale and modelled products such as pressure vessels and pipeline elements tested at low climatic temperatures of Yakutsk. This testing site consists of a bunker measuring 3 x 12m and 3m in depth, having special supports for the products fixation, and a hydraulic loading system together with metering lines and devices (Fig. 5). An arctic diesel fuel was used as a working medium for hydraulic testing. The computing-metering complex includes an automated system of measuring, recording and mathematical computer-aided treatment of data. The software package consists of several subroutines: monitoring subprogram, subprogram of initial data treatment, subroutine of stress- and strain computing, subroutine of strain gauge reading control, and that of pressure gauge reading control.

According to the results of a series of full-scale testing of pipeline elements made from 17Г1C and 14 2CAФ steels 15 and 11mm thick containing machined notches, as well as to the results of full-scale pipe testing published in [5, 6], critical values of circumferential stress $\sigma_{oc}$ were determined.
Fig. 5. Block diagram of a system for testing real products and their models such as pressure vessels and pipeline elements:
1- operator communication (display); 2- program entry (photoreader); 3- data entry (perforator); 4- printer; 5- microprocessor; 6- interface; 7- ADC; 8- digital bridge; 9- amplifier; 10- commutator; 11- pressure gauge (from the loading system).

The data of full-scale tests of pipeline sections from 17Γ1C and 14Γ2CAΦ steels were compared with the results of laboratory tests of plates with central crack. Fig. 6 shows a relationship between the value \( \frac{1}{J} \left( \frac{K_c}{\sigma_{0.2}} \right) \) which represents a parameter of fracture resistance of pipes having a longitudinal notch of length 21, and the value \( \left( \frac{\sigma_{0.2}}{\sigma_{0.2}} \right)^2 \) which is a design parameter of a pipe with longitudinal notch. Averaged results of full-scale tests of pipeline sections can be approximated to take a linear dependence on a material crack resistance parameter defined from the laboratory tests. On this basis, a lower boundary criterion for pipeline carrying capacity is derived.
When using (2) to determine the circumferential stress produced at a given procedure of pipeline welding, it is possible to find a safety margin factor arising from the given welding procedure, i.e. from the choice of base and filler materials:

$$\alpha_{m} = \frac{\sigma_{r}}{\sigma_{\theta}}.$$  \hspace{1cm} (3)

2.1. Ageing of polymers

Comparing the results of polymer atmospheric durability assessment in different climatic zones of the USSR (Moscow, Tashkent, Batumi, Yakutsk), we have come to the conclusion that most materials are influenced by warm humid and hot dry climates [3]. At the same time, a less intensive ageing of structural polymers in the conditions of cold climate is in an obvious contradiction with low serviceability and longevity of machines and mechanisms used in the North. This is mainly due to the fact that the currently available methods of material atmospheric durability estimation as applied to cold climate conditions does not allow even a qualitative assessment as they are based on the test results derived at room temperature while the products are used at temperatures -50...-60°C[14].

The gist of this phenomenon which we named as "frost effect" consists in the following.

As known, the climatic ageing of polymers should be considered as an accumulation of different flaws: surface microcracks, pores,
delaminations etc. caused by atmospheric moisture, ultraviolet radiation, temperature difference and by other factors. It is evident that an increase in material damage decreases the strength properties at the cost of a material brittleness rising. Moreover, tests conducted at normal temperatures allow the strength decreasing to be revealed only in the presence of sufficiently large cracks since a relatively rapid relaxation of local over-stresses in the weakened "defective" site contributes to the crack "healing" and original strength recovery.

On the other hand, low temperature tests of aged specimens make it possible to detect microcracks of very small sizes that can be concentrators of local overstresses which do not relax beyond the crack vicinity but do promote a critical stress concentration at the crack tip. In turn, vanishing of microstrains in material results in degeneration of quasi-brittle fracture mechanism and displacement of the brittle fracture temperature to that of quasi-brittle fracture.

2.2. Welding

It is shown that welding procedures adopted for the above- and subzero temperatures have significant differences[11]. Thus, when welding at temperatures below -40°C the arc plasma temperature on the discharge axis increases by 780-840°C and the coefficient of arc heat input rises by 6-8%. Hydrogen diffusion from welds is 30-40 times lower and their cold cracking resistance diminishes by 10-40%. At 600-500°C the cooling rates increases by 25-40% and are 1.6-2 times faster at 300°C. According to the specific heat input, the time of weld metal keeping in the range of 300-100°C is 2-4 times shorter. This results in reduction of phase and structure transformation temperatures by 20-40°C. As a consequence, the critical brittleness temperature is shifted to the direction of above zero temperatures by 15-35°C.

On the basis of comprehensive tests of joints made in a wide range of welding conditions, optimum heat input levels were established and residual hydrogen content in weld for a given combination of base and filler materials were specified.

Thus, when fabricating structures by electric arc welding, in addition to the requirement of satisfactory weld shaping and obtaining the full strength joint they should meet some
specific requirements according to combined criteria that characterize, at least, the three basic physical-mechanical factors: brittle fracture resistance of joints, resistance to cold cracking and fatigue strength. All those factors are interrelated. Thus, even in presence of minor cold cracks or fatigue flaws under variable loading the weld susceptibility to brittle fracture significantly varies: this is especially clearly seen at temperature lowering.

3. CONCLUSION

At present, there is a lot of research results that can be used as a basis for solving some engineering problems when developing machinery and structures for North scope applications. The same holds true for material science (steels, cast alloys, polymer and composite materials, fuel and lubricants and so on), for problems of design, fabrication, hardfacing and repair, including welding technology, as well as for plasma, detonation, vibration, laser treatment and, finally, for development of calculation methods of serviceability prediction, structure carrying capacity estimation etc. Along with fundamental studies in this field it is reasonable on the basis of available results to precipitate the development of corresponding codes and standards.

4. REFERENCES


SOME EXPERIMENTAL OBSERVATIONS ON CONCRETE BEHAVIOR
AT LOW TEMPERATURE

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ABSTRACT

Experimental studies were carried out on Young's modulus, Poisson's ratio, compressive strength and local bond strength (under monotonic, repeated cyclic, and reversed cyclic loadings) of normal and high-strength concrete in the temperature range of 20°C and -70°C (68°F and -94°F). Results show that the values of Young's modulus, Poisson's ratio and local bond strength increase with concrete compressive strength as the temperature decreases. Furthermore, the rate of increase in values for high-strength concrete is generally lower than that for normal strength concrete. Based on the experimental observations, values for Young's modulus, Poisson's ratio, and local bond strength of concrete at low temperature as functions of concrete compressive strength are determined by regression analyses. Attempts are also made to express these three properties for both normal and high-strength concrete in single functional forms of the concrete compressive strength.

1. INTRODUCTION

In recent years cold regions engineering research has become an important area of study because of the emphasis given to resource development. Although much experience-based information is available for design engineers, insufficient knowledge is available on the basic mechanical properties of concrete at low temperature. Two series of laboratory studies were conducted at SUNY/Buffalo on compressive strength, static modulus of elasticity, Poisson's ratio and local bond strength between concrete and steel, under monotonic and cyclic loadings, for both normal and high-strength concrete.
Specimens were tested in the temperature range of 20°C to -70°C (68°F to -94°F). Furthermore, laboratory observations were also made on the effects of freeze-thaw temperature cycles on the mechanical properties of concrete. Details of these studies are reported separately (2-6). This present paper is a summary of the results and conclusions reported in these publications.

2. EXPERIMENTAL PROGRAM

2.1 Test Specimens

Thirty-two sets (94 specimens) of normal strength concrete (NSC) and fifty-five sets (162 specimens) of high-strength concrete (HSC) specimens were tested for compressive strength, Young's modulus and Poisson's ratio at normal temperature (+20°C) as well as at low temperatures of -10°C, -30°C, -50°C, and -70°C. In addition, sixteen sets (48 specimens) of normal strength concrete specimens were experimentally investigated for the effects of freeze-thaw cycles on concrete compressive strength, Young's modulus and Poisson's ratio. Twenty-five specimens of normal strength concrete and thirty-two specimens of high-strength concrete were tested for local bond stress-slip relationship of deformed bars embedded in confined concrete under monotonic and cyclic loadings in the temperature range between +20°C and -70°C. Additionally, three groups of specimens were tested for the effect of freeze-thaw cycles on the bond behavior between steel reinforcement and normal strength concrete. Specially designed 7 x 12 x 12 in (178 x 305 x 305 mm) reinforced concrete blocks with Grade 60 deformed bars of bamboo style (lug geometries) were used for the test of local bond strength. Both the normal and high-strength concrete were air-entrained with designed twenty-eight day compressive strengths of 5500 psi (37.92 N/mm²) and 9000 psi (62.06 N/mm²) respectively. The materials used for the concrete were typical mixes and are described in References 2 and 3. All the specimens were cured in a fog room at 23°C ± 1.9°C (73.4°F ± 3°F) and 100% relative humidity from the time of molding until testing under normal temperature or until placing the specimens in the freezer for cooling (four weeks for NSC and nine weeks for HSC).

A total of seven batches of high-strength concrete and nine batches of normal strength concrete were used for the experimental investigation.

2.2 Method of Testing

The testing procedures of concrete compressive strength, Young's modulus and Poisson's ratio strictly followed ASTM standards. A Tinius Olsen testing machine of 300 kips (1334 KN) capacity was used for standard
cylindrical specimens. Combined compressometer-extensometer, Tinius Olsen electronic recorders and strain instrumentation were used for measuring the deformations. The stress-longitudinal strain (or load-longitudinal deformation) curves were automatically plotted by the Tinius Olsen Mold 51 electronic high magnification recorder.

For local bond test, specimens were 7 x 12 x 12 in (178 x 305 x 305 mm) blocks. A special testing device was used to anchor the specimens to the test floor. The details of loading procedures are described in Reference 4. The bonded bar was axially loaded in tension at either end by two MTS actuators. Loads and displacements were automatically controlled by a MTS controller. All test data were acquired and stored in a computer during testing.

All specimens were tested under normal temperature (+20°C), and four different levels of low temperature (-10°C, -30°C, -50°C and -70°C). The temperature of the specimens during the test was controlled within the following limits: -70°C ± 3°C, -50°C ± 2°C, -30°C ± 1°C, and -10°C ± 0.5°C. Each specimen was instrumented with copper constantan thermocouples close to the bonded region to monitor the specimen temperature during the test.

3. TEST RESULTS

3.1 Compressive Strength

The average value of compressive strength of high-strength concrete at normal temperature is 9550 psi and that for the normal strength concrete is 5740 psi. For both normal and high-strength concrete the compressive strength increases uniformly as the temperature decreases because of the presence of ice in the pore spaces in the cement paste matrix. However, the rate of increase of compressive strength of high strength concrete as the temperature decreases is slow than that of the normal strength concrete.

3.2 Young's Modulus

The values of the static modulus of elasticity of all the specimens for normal and high-strength concrete at different low temperatures are obtained according to ASTM C-469, which measures the static chord modulus of elasticity made at 40% of the ultimate load of the load-deformation curve. Based on these experimental data, an empirical equation for the Young's modulus in terms of concrete compressive strength at low temperature was determined by computer regression analysis using the least square method. It is given by:

\[ E_c = 62,000 \cdot \sqrt{f'_c} - 710,000 \text{ psi} \]

for 5,000 psi \( \leq f'_c \leq 16,000 \text{ psi} \)
or

\[ (E_c = 5,060 \sqrt{f_c'} - 4,920 \text{ MPa} \]
\[ \text{for } 35 \text{ MPa} < f_c' < 110 \text{ MPa} \]

It is noted that if the experimental data of all 127 specimens (basis for Eq. 1) are combined with those of 217 specimens used for deriving the Young's modulus at normal temperature, the Young's modulus for both normal strength and high strength concrete at normal and low temperatures may be written as a single function of the concrete compressive strength.

\[ E_c = 59,000 \sqrt{f_c'} - 420,000 \text{ psi} \]  
\[ \text{for } 3,000 \text{ psi} < f_c' < 16,000 \text{ psi} \]

or

\[ (E_c = 4,800 \sqrt{f_c'} - 2,360 \text{ MPa} \]
\[ \text{for } 21 \text{ MPa} < f_c' < 110 \text{ MPa} \]

The line represented by Eq. (2) is very close to the line representing the empirical equation for Young's modulus of concrete at normal temperature only (Fig. 1). This signifies that the Young's modulus may be expressed only in terms of concrete compressive strength regardless of the temperature level.

Figure 1. Modulus of elasticity vs. concrete strength
3.3 Poisson's Ratio

Data of 86 specimens of high-strength concrete and 25 specimens of normal strength concrete were obtained for Poisson's ratio under -10°C, -30°C, -50°C and -70°C. Based on the experimental results, an empirical equation for Poisson's ratio in terms of concrete compressive strength determined by computer regression analysis using least square method is given by:

\[
\nu = 0.00115 \sqrt{f'_c} + 0.140
\]

(\(f'_c\) in psi)

for 7,000 psi < \(f'_c\) < 16,000 psi

Again, if the experimental data of all specimens for Poisson's ratio at normal temperature and at various low temperature levels are combined in the regression analysis, the Poisson's ratio in terms of concrete compressive strength may be written as:

\[
\nu = 0.00164 \sqrt{f'_c} + 0.082
\]

(\(f'_c\) in psi)

for 5,000 psi < \(f'_c\) < 16,000 psi

or

\[
\nu = 0.02f'_c + 0.08
\]

(\(f'_c\) in MPa)

for 35 MPa < \(f'_c\) < 110 MPa

Equation (4) lies between the individual lines representing the equations for Poisson's ratio at normal and low temperature respectively. The correlation coefficient for the combined empirical equation is much better than those for the individual cases. Therefore, Eq. (4) is appropriate for Poisson's ratio for all temperature levels.

3.4 Local Bond Strength

As pointed out in References 4 and 5, it is more appropriate to use local bond strength as the design basis in structural connection regions. The local bond strength of deformed bars embedded in confined concrete generally increases as the temperature decreases under monotonic, repeated cyclic and reversed cyclic loadings. Detailed test results of local bond strength for normal and high-strength concrete are given in References 4 and 5 respectively. Based on these experimental data, our empirical equation for local bond strength of concrete under monotonic loading at low temperature may be expressed in terms of compressive strength as
If the experimental data of all the specimens under monotonic loading at normal temperature are combined with those at low temperature, a combined empirical equation for the local bond strength in terms of concrete compressive strength may be written as

\[ \tau_{\text{max}} = 112 \sqrt{f'_c} - 5,000 \text{ psi} \]  
\hspace{1cm} \text{for } 8,000 \text{ psi} < f'_c < 14,000 \text{ psi} 

or

\[ \tau_{\text{max}} = 9.30 \sqrt{f'_c} - 34.50 \text{ MPa} \]  
\hspace{1cm} \text{for } 55 \text{ MPa} < f'_c < 100 \text{ MPa} 

The lines representing Eqs. (5) and (6) are practically identical. Therefore, the local bond strength may also be expressed in terms of concrete compressive strength independent of the temperature level. Similarly, all the bond stress-slip curves for the specimens under monotonic, repeated cyclic and reversed cyclic loadings are only affected by the increase of concrete compressive strength as the temperature decreases.

3.5 Effect of Freezing Cycles

In the experimental program a number of specimens experienced 1, 10, and 30 freeze-thaw cycles before tests\(^{(2,7)}\). The cyclic temperature change was from +8°C (+46°F) to -52°C (-62°F) in 24 hours. The experimental results show that freeze-thaw cycles will reduce the compressive strength, Young's modulus and Poisson's ratio of concrete, when compared with their values at normal temperature. Cyclic temperature changes have a decisive influence on the maximum bond resistance and the shape of the bond stress-slip relationships for reversed cyclic loading. The energy dissipation capacity of the specimens under reversed cyclic loading with freezing cycles is considerably reduced.

Because of the lack of information and the practical importance in designing structures in low temperature zones, the effect of freeze-thaw cycles on concrete strength is presently examined systematically at SUNY/Buffalo.
4. SUMMARY

The observations made in this experimental study may be summarized in the following.

1) The compressive strength of concrete increases uniformly as the temperature decreases but the rate of increase in the compressive strength for high strength concrete is lower than that for normal strength concrete.

2) The rate of increase in Young's modulus at low temperature is smaller than that for the compressive strength. The value of Poisson's ratio increases with the compressive strength of the concrete as the temperature decreases. Furthermore, the Poisson's ratio is definitely higher for higher-strength concrete.

3) For repeated cyclic loading the maximum bond stress is generally lower than that of monotonic loading at the same low temperature.

4) For reversed cyclic loading the average of the maximum bond stresses in both directions is significantly lower than that for monotonic loading at the same low temperature.

5) Young's modulus, Poisson's ratio and local bond strength may be expressed in terms of concrete compressive strength by disregarding the temperature factor. Combined empirical formulas for Young's modulus, Poisson's ratio and local bond strength of concrete under normal and low temperature are suggested.

6) Cyclic temperature changes appear to have a decisive influence on the maximum bond resistance and the shape of the bond stress-slip relationships under reversed cyclic loading. The energy dissipation capacity of the specimens under reversed cyclic loading with freezing cycles is considerably reduced.

7) The effect of cyclic temperature changes on the mechanical properties of concrete should not be neglected in reinforced concrete design in seasonably cold regions with freezing cycles.

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REFERENCES


EXTRA HIGH STRENGTH STRUCTURAL STEELS FOR ICE BREAKERS

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SWEDEN

ABSTRACT

For an ice breaker hull the primary design factors are high lateral pressure caused by ice and weld corrosion. By utilizing modern plate manufacturing methods extra high strength structural steels with low temperature toughness and excellent weldability can be produced.

The arctic grade of WELDOX 500 (former OX 602) has a yield strength of 500 MPa and good toughness down to a temperature of -60C. The chemical analysis is chosen to withstand weld corrosion. WELDOX 500 also exists as compound plate with stainless steel explosion welded on.

By utilizing WELDOX 500 the total economy of an icebreaker hull can be kept low. Example of savings are:

* Low maintenance cost, no corrosion
* Low fabrication costs - low preheating costs
  - reduced weld volumes
  - increased stiffener spacing
  - reduced hull plate thickness
  - easier surface treatment
* Low transport/handling costs - low steel weight
* Increased loading capacity of the icebreaker - low hull weight.
EXTRA HIGH STRENGTH STRUCTURAL STEELS FOR ICE BREAKERS

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Enclosure 1: WELDING PROCEDURE DATA SHEET WELDOX 500-316 L

840
1. INTRODUCTION

A continuous development of production techniques and process control, together with improved knowledge of the combined effect of different alloying elements, make it possible to produce thermomechanically treated steels (TM) and Quenched and Tempered (QT) steels with yield stresses up to 960 MPa, with good toughness and good weldability.

In this paper the new generation icebreaker steel, WELDOX 500, (new designation for OX 602), will be presented. The steel is a NV 500-type steel and possesses properties which can give good overall structural economy.

2. STEEL PROPERTIES

Quenching and tempering in combination with microalloying results in a fine grain microstructure. Grain refinement is the only metallurgical way to both increase strength and toughness. Roller quenching of the steel will give a rapid cooling and a small grain size even if the alloying content is low.

Through the QT-process it is then possible to produce a high strength steel with good toughness and weldability.

2.1 Mechanical properties

Table 1. Guaranteed properties of WELDOX 500

<table>
<thead>
<tr>
<th>Thickness (mm)</th>
<th>Re min (MPa)</th>
<th>Rm (MPa)</th>
<th>A5</th>
<th>CV1 transv -60C (J)</th>
<th>2-properties min (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 -50</td>
<td>500</td>
<td>610-770</td>
<td>16</td>
<td>40</td>
<td>35</td>
</tr>
<tr>
<td>(50)-80</td>
<td>480</td>
<td>590-750</td>
<td>16</td>
<td>40</td>
<td>35</td>
</tr>
</tbody>
</table>

The typical toughness properties are shown as a transition curve for a 40 mm thick plate in figure 1. The steel remains ductile for temperatures down to -60 C.
Figure 1. Charpy V-notch transition curve.

2.2 CHEMICAL ANALYSIS

The alloying concept for WELDOX 500 is based on a low carbon content and micro alloying with Ti-V.

The aim analysis for the steel is given in Table 2. A typical NVE36 analysis is given as comparison.

Table 2. Aim analysis for WELDOX 500 and NVE36.

<table>
<thead>
<tr>
<th>Steel grade</th>
<th>C (%)</th>
<th>Mn (%)</th>
<th>Si (%)</th>
<th>P (%)</th>
<th>S (%)</th>
<th>Cr (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NVE36</td>
<td>0,15</td>
<td>1,42</td>
<td>0,43</td>
<td>0,015</td>
<td>0,015</td>
<td>-</td>
</tr>
<tr>
<td>WELDOX 500</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>t &lt; 60 mm</td>
<td>0,13</td>
<td>0,9</td>
<td>0,25</td>
<td>0,010</td>
<td>0,003</td>
<td>0,20</td>
</tr>
<tr>
<td>t &gt; 60 mm</td>
<td>0,09</td>
<td>0,9</td>
<td>0,25</td>
<td>0,010</td>
<td>0,003</td>
<td>0,20</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Steel grade</th>
<th>Ni (%)</th>
<th>Cu (%)</th>
<th>Ti (%)</th>
<th>V (%)</th>
<th>Nb (%)</th>
<th>CE *) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NVE36</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0,025</td>
<td>0,41</td>
</tr>
<tr>
<td>WELDOX 500</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>t &lt; 60 mm</td>
<td>0,40</td>
<td>0,25</td>
<td>0,012</td>
<td>0,050</td>
<td>-</td>
<td>0,38</td>
</tr>
<tr>
<td>t &gt; 60 mm</td>
<td>1,5</td>
<td>0,20</td>
<td>-</td>
<td>0,03</td>
<td>-</td>
<td>0,43</td>
</tr>
</tbody>
</table>

*) $CE = C + \frac{Mn}{6} + \frac{(Cr + Mo + V)}{5} + \frac{(Ni + Cu)}{15}$
3. WELDABILITY

The low carbon content and micro alloying with Ti and V improve the weldability in comparison with an ordinary NVE36 with Nb-alloying (table 2).

From various welding trials a welding diagram has been produced (Figure 2). HAZ embrittlement is defined as Charpy impact energy lower than 40 J at -40°C. Cracking is defined when hydrogen cracks occur after welding and no preheating has been applied. For normal workshop practice welding can be performed without preheating in plate thicknesses up to 50 mm.

![Welding diagram for WELDOX 500.](image)

Figure 2. Welding diagram for WELDOX 500.

As an example of the weldability a 50 mm thick WELDOX 500 was butt joint welded. Submerged arc welding was used and the welding parameters were set to give a heat input of 3.1 kJ/mm. No preheating was applied. The joint was then impact tested. The results were well above 40 J at -60°C in the HAZ. The test results are shown in Figure 4. In Figure 5 test results from an equivalent test made on a NVE36 steel is shown.

![Impact test results, WELDOX 500, transverse.](image)

Figure 3. Impact test results, WELDOX 500, transverse.
Icebreakers have their paint coating and cathodic protection system destroyed by contact with ice. This will cause local corrosion of welds which results in high maintenance costs.

The corrosion is caused by galvanic action between weld metal and the plate. The corrosion can more or less be prevented if the electrochemical potential between weld metal and plate is close to zero or having weld metal slightly cathodic.

Together with Wärtsilä OY, Finland, and ESAB a corrosion test program was conducted according to paragraph XIV-4.3.2.6 in the USSR Register's Rules. Ten test panels were welded and positioned on a rotator. A reference panel in NVE36 welded with an AWS E7018 electrod (ESAB OK 48.00) was included in the test. The assembly was then lowered into a seawater tank. During rotation the waterspeed on the plates were approximately 4 m/s.

The water was changed weekly and had a temperature of 25 C. The duration of the testing was 2400 hours (= 3,3 months). Test results are evaluated by visual inspection of the panels.

The test results (Table 3) show that filler metals with a Ni-content of 2-3 % will not give weld corrosion. Filler materials with 1 % Ni will give slight corrosion. Weld metal is then not enough cathodic.
Table 3. Result of local corrosion test

<table>
<thead>
<tr>
<th>Base Metal</th>
<th>Welding consumable</th>
<th>Test Results *)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NVE36</td>
<td>OK 48.00</td>
<td>WM 3 HAZ 0 BM 0</td>
</tr>
<tr>
<td>WELDOX 500</td>
<td>OK 73.68</td>
<td>WM 0 HAZ 0 BM 0</td>
</tr>
<tr>
<td>&quot;-</td>
<td>OK 73.79</td>
<td>WM 0 HAZ 0 BM 0</td>
</tr>
<tr>
<td>&quot;-</td>
<td>Filarc 885</td>
<td>WM 1 HAZ 0 BM 0</td>
</tr>
<tr>
<td>&quot;-</td>
<td>Speedarc</td>
<td>WM 0 HAZ 0 BM 0</td>
</tr>
<tr>
<td>&quot;-</td>
<td>X81 TG-Ni2</td>
<td>WM 0 HAZ 0 BM 0</td>
</tr>
<tr>
<td>&quot;-</td>
<td>Dual shield</td>
<td>WM 1 HAZ 0 BM 0</td>
</tr>
<tr>
<td>&quot;-</td>
<td>1180 Ni 1</td>
<td>WM 1 HAZ 0 BM 0</td>
</tr>
<tr>
<td>&quot;-</td>
<td>OK Tubrod 14.04</td>
<td>WM 0 HAZ 0 BM 0</td>
</tr>
<tr>
<td>&quot;-</td>
<td>OK Tubrod 15.17</td>
<td>WM 1 HAZ 0 BM 0</td>
</tr>
<tr>
<td>&quot;-</td>
<td>OK Autrod 12.24</td>
<td>WM 0 HAZ 0 BM 0</td>
</tr>
<tr>
<td>&quot;-</td>
<td>OK Flux 10.62</td>
<td>WM 0 HAZ 0 BM 0</td>
</tr>
<tr>
<td>&quot;-</td>
<td>OK Tubrod 13.27</td>
<td>WM 0 HAZ 0 BM 0</td>
</tr>
<tr>
<td>&quot;-</td>
<td>OK Flux 10.62</td>
<td>WM 0 HAZ 0 BM 0</td>
</tr>
</tbody>
</table>

*) 0 = No corrosion, 1 = Slight corrosion, 2 = Clear corrosion, 3 = Heavy corrosion

WM = Weld metal, HAZ = Heat affected zone, BM = Base material

5. COMPOUND PLATE

In collaboration with Avesta AB and Nitro Nobel, SSAB Oxelösund has developed a compound grade between WELDOX 500 and a 316 L stainless steel. The stainless layer is explosion welded on WELDOX 500.

The compound steel will prevent corrosion in the splash zone. The maintenance cost for the hull will then be further reduced in comparison with the corrosion resistant arctic grade of WELDOX 500.

The weldability of the compound plate will be governed by WELDOX 500. A 50 mm thick with a layer of 4 mm 316 L has been test welded with excellent results. In enclosure 1 welding procedure and test results are shown.

Fig 5 shows specimen locations and fig 6 impact test results.
The primary design factor for an icebreaker hull is the lateral pressure caused by ice.

For ODEN, the new Swedish icebreaker, WELDOX 500 was chosen for the hull. By utilizing the strength of the steel stiffener spacing could be increased from 350 mm to 850 mm. Almost 2/3 of the fillet welds could then be saved by reducing the amount of stiffeners.
In fig 7 it can be seen how the strength affects the spacing in a simple calculation example. The example is a bottom plate on 20 m depth and only water pressure is regarded.

Figure 7. Relationship plate thickness - steel strength - spacing for a bottom plate at 20 m water depth.

Due to the weldability GVA (fabricator of ODEN) welded the hull without applying preheating for plate thicknesses up to and including 50 mm. According to GVA they saved 3 milj SEK in preheating cost compared with if the hull was made of a NVE36-steel.

Other possible savings by the increased steel strength can be:

* reduced transportation/handling cost due to reduced steel weight
* larger prefabricated sections or more outfitted sections due to reduced steel weight
* easier blastcleaning and painting when increased stiffener spacing is utilized
* increased loading capacity due to low hull weight
CONCLUSION

Through modern plate manufacturing systems plate for various requirements can be manufactured.

The arctic grade of WELDOX 500 has a yield strength of 500 MPa with good low temperature properties. With proper heat treatment the chemical analysis can be kept leaner as an ordinary 355 MPa steel. This will give the steel an excellent weldability. With a proper alloying concept the detrimental weldment corrosion on icebreaker hulls can be avoided. The safest way to avoid the corrosion is to use compound plate of WELDOX 500/stainless in the splash zone.

By utilizing WELDOX 500 in artic structures many advantages can be reached, examples are:

* reduced weld volumes and structural steel weight by either increasing stiffener and web spacing or reducing plate thickness
* reduced preheating cost thanks to a low carbon equivalent, excellent weldability. On the new Swedish icebreaker, ODEN, 3 milj SEK was saved
* reduced transportation/handling costs of steel and steel sections due to low steel weight
* larger prefabricated sections or more outfitted sections due to low structural weight
* easier surface treatment, blast cleaning, painting, inspection and maintenance when increased stiffener spacing is utilized
* increased loading capacity due to low hull weight
9. REFERENCE LIST


# Welding Procedure & Data Sheet for Compound Ox602-3/6L

## Grade: Ox602-3/6L

### Internal Grade:
- Ox 602

### Heat No.:
- 73391-24.6

### Properties:
- E = 673 N/mm²
- Rm = 629 N/mm²
- A5 = 12 %
- CV = JOULE at °C

### Chemical Composition:

<table>
<thead>
<tr>
<th>Element</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>V</th>
<th>Cu</th>
<th>Ti</th>
<th>Al</th>
<th>Nb</th>
<th>N</th>
<th>B</th>
<th>O</th>
<th>L</th>
<th>W</th>
<th>CE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.09</td>
<td>0.24</td>
<td>0.03</td>
<td>0.004</td>
<td>0.018</td>
<td>0.016</td>
<td>0.015</td>
<td>0.034</td>
<td>0.018</td>
<td>0.014</td>
<td>0.015</td>
<td>0.004</td>
<td>0.001</td>
<td>0.005</td>
<td>0.007</td>
<td>0.012</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Welding Consumables:
- ESAB OK 12.24 + Flux OK 17.61

### Welding Process:
- Layer 1: Avesta P5 AC/DC
- Layer 2: SKR AC/DC

### Welding Conditions:

<table>
<thead>
<tr>
<th>No.</th>
<th>Preheat °C</th>
<th>Interpass °C</th>
<th>200/100</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Welding Results:
- Fracture position: Max HV 5 (HAZ)

### Mechanical Test:
- Traverses 5mm below stainless surface
- Traverses 2mm below stainless weld surface
- Hardness acc. to ISO 6507 HS

### Diagram:
- Layer 2-3

---

850
Mechanical Test Results

Specimen: P1

Internal Grade: Heat No: 1-504-437

Welding Procedure & Data

S Ellison
This paper focuses on the experimental results of the thermal behaviour of concrete and bond between reinforcement and concrete at very low temperatures down to -165°C. The aim of the experimental investigation is to determine the bond stress-slip relationships with the aid of a pull-out test as a function of the temperature and moisture content of the concrete. Typical features associated with low temperatures will be discussed, particularly at -40 and -80°C. It is found that for sealed and air-dry concrete crack width and crack spacing can be predicted at low temperatures with the aid of classical formulae.

1. INTRODUCTION

The arctic and subarctic environment is characterized by severe loading conditions at low temperatures down to about 50 degrees Celsius below zero. Even lower temperatures are commonly used for cryogenic storage, Bruggeling (1979). To support the application of reinforced concrete in such an environment more information about material properties and crack phenomena are needed.

Because bond between the concrete and reinforcement and the tensile (splitting) strength of concrete are the most essential properties that determine crack spacing and crack width, experiments were conducted to observe the characteristic features of these properties at very low temperatures.

Reinforced concrete made with silicious aggregates shows more or less the same thermal expansion as the reinforcement in the temperature range from -20 to +60°C. However, when reinforced concrete is used beyond the temperature range stated above, the thermal expansion may differ considerably. As a result of the differential thermal deformations high internal restraint stresses would occur and could affect, among other
features, crack spacing and crack width. For that reason the thermal behaviour of concrete is also examined.

Furthermore, a number of experiments were performed on centrically reinforced specimens subjected to direct tension, to investigate crack width and spacing.

2. EXPERIMENTAL PROGRAM

The bond stress-slip relationship was determined on concrete (at an age of 90 days), by means of a pull-out test with an embedment length of 3 times the bar diameter. Cylindrical concrete specimens reinforced centrically with a 20 mm diameter deformed bar were used. The minimum yield stress at room temperature is 470 N/mm$^2$ and the relative rib area $f_R$ is about 0.076.

For measuring the thermal contraction and expansion behaviour a 60 mm x 150 mm cylindrical specimen of concrete or a reinforcing bar 150 mm in length was used in the experiments.

A number of experiments were performed on centrically reinforced specimens of 1000 mm in length. These specimens, with 100 mm x 100 mm square cross-sections, were reinforced with one deformed bar of 20 mm diameter and subjected to direct tension at different temperatures.

The specimens were cooled at a constant rate (1°C/min) with the aid of liquefied nitrogen (-196°C). More details about the applied testing, cooling and measuring techniques are described in Van der Veen (1987b).

2.1 Experimental variables

From a preliminary study Van der Veen (1987a), it is concluded that the temperature and the moisture content of the concrete mainly affect the properties of concrete. Therefore the temperature and the moisture content are the main variables to be investigated. The basic experimental program comprised the following variables:

Temperature
Generally, five different temperatures +20, -40, -80, -120 and -165°C respectively were applied.

Concrete grade
Two different concrete mixes were used with average 28-day cube compressive strengths of approximately 60 (Mix 1) and 40 N/mm$^2$ (mix 2). The two mixes contained Portland Cement-B and glacial river aggregates having a 16 mm maximum grain size and a grading curve according to Fuller.

Curing conditions
Three different conditions were applied: water-saturated (S), sealed (W) and air-dry concrete at 50% relative humidity (H).
3. EXPERIMENTAL RESULTS
3.1 Thermal behaviour

The effect of three different sets of curing conditions namely, water-saturated, sealed and air-dry at 50% r.h., upon the thermal strain-temperature relationship was investigated. Experimental results for both mixes determined at an age of 90 days are shown in Fig. 1, where each curve represents the mean of three different experiments.

Specimen, which were sealed or air-dried during the curing time exhibited almost linear thermal deformation and perfect reversibility. The thermal deformations for both mixes were almost identical, so the water/cement ratio did not affect the thermal behaviour. However, the water-saturated specimens showed totally different behaviour. Between -20 and -60°C a pronounced expansion was observed. This expansion in the transition range was clearly influenced by the water/cement ratio and increased for higher ratios, as Fig. 1 shows. When the water-saturated specimens were reheated, even greater expansion occurred, and irreversible strains indicating internal micro-cracking were observed at 20°C after reheating. These irreversible strains are greatest for the concrete mix with the highest water/cement ratio.

![Figure 1. Thermal strain and coefficient of thermal expansion as a function of temperature.](image)
The sealed specimens were tested at two different ages, namely, 90 and 365 days. The concrete at an age of 365 days was found to have a thermal strain which was slightly greater than that of concrete at an age of 90 days. Furthermore, it shows perfect reversibility from cooling to reheating.

To investigate the influence of the type of steel upon the thermal deformation, three different steels, namely, Krybar, Krybar with 3.5% Ni and Tempcore were tested. Only minor differences between the different types of steel were found to occur during cooling. Some typical results represented by one line are shown in Fig. 1.

For engineering calculations it is common to define the coefficient of thermal expansion $\alpha(T)$ as the slope of the secant with the origin at 20°C:

$$\alpha(T) = \frac{\varepsilon(T)}{(T-20°C)}$$

in which $\varepsilon(T)$ = thermal strain and $T$ = temperature

For air-dry and sealed concrete a continuously decreasing curve was found. The shaded area gives the scatter range for both mixes. It turned out that changes in the moisture content have virtually no effect on the thermal deformation. When we compare the coefficient of expansion of the reinforcement and concrete, it is clear that only limited stresses will be introduced in a reinforced member.

The water-saturated concrete showed an expansion in the transition range which greatly depended on the water/cement ratio or moisture content (m). For the two concrete mixes investigated, with water/cement ratio of 0.40 and 0.60 respectively, a positive value of $\alpha_c(T)$ was always found, see Fig. 1.

![Graph](image-url)  

**Figure 2.** Tensile splitting strength for mix 2 with different moisture content versus temperature.
3.2 Tensile splitting and compressive strength

The tensile splitting strength shows a marked increase for water-saturated and sealed concrete in the temperature range from 0 to -40°C, particularly for mix 2. In general a maximum value was observed at -80°C, see Fig. 2. At lower temperatures the increase in strength remained constant or even a small decrease was observed, as shown in Fig. 3. For comparison, results by Goto and Miura (1978) are shown in Figs. 2 and 3 which are close for mix 1 but underestimated the moisture influence for mix 2.

\[
f_{cspl} (N/mm^2) = \begin{cases} 12 & \text{water-saturated} \\ 1.8 & \text{sealed} \\ 1.4 & \text{air-dry 50% rh} \\ \end{cases}
\]

Figure 3. Tensile splitting strength for mix 1 with different moisture content versus temperature.

Investigations (Wiedemann, 1982) have shown that the compressive strength increases as the temperature is lower. This increase is hardly affected by the strength at room temperature, i.e. mix proportions, curing method, or age of the concrete. For this reason the mean compressive strength at low temperatures can be expressed as:

\[
f_{cm}(T;m) = f_{cm}(20°C) + \Delta f_{cm}(T;m) \quad N/mm^2 \tag{2}
\]

in which the strength increase \( \Delta f_{cm}(T;m) \) depends on temperature and moisture content only. Basing himself on experimental research, Rostásy (1984), derived a formula, similar to the one derived by Goto and Miura (1978), to predict the increase in compressive strength:

\[
\Delta f_{cm}(T;m) = (1 - \left(\frac{T + 170}{170}\right)^2) \times 12 \times m \quad N/mm^2 \tag{3}
\]

in which \( m = \) moisture content % (by wt)

\( T = \) temperature °C
Formula (3) shows reasonably good agreement with the experimental values for both mixes, as presented in Fig. 4. Note, that formula (3) was originally developed for the cylinder strength.

Figure 4. Increase in compressive strength at 90 days versus temperature.

3.3 Bond stress-slip relationship

The influence of the temperature upon the bond stress-slip \( (\tau_b - \Delta) \) relationship experimentally found is clearly shown in Fig. 5. Only small crack widths are important for practical conditions. Hence, attention was more particularly focussed on small slip values.

How the curing conditions affect the bond stress-slip relationships can be seen in Fig. 5. The air-dry concrete specimens give the lowest bond resistance, while hardly any difference could be observed for the water-saturated and the sealed specimens. However, the bond resistance is always larger than the bond resistance determined at room temperature.

An attempt was made to predict the local bond stress-slip curves analytically. Therefore the curves were approximated by the expression:

\[
\tau_b(T) = a(T) \Delta^{b(T)} \quad \text{N/mm}^2 \tag{4}
\]

This formula was originally suggested by Noakowski (1978) for application at room temperature.
Figure 5. Bond stress-slip relationship for different curing conditions and temperatures.

Typical factors of the bond stress-slip relationship are shown in Fig. 6. The exponent b varied from 0.42 to 0.51 in the temperature range from 20°C to -80°C. Comparable values for the exponents were found by Rostásy and Scheuermann (1984). However, at -40°C a mean value of 0.48 could be adopted for all curing conditions.

Figure 6. Factors of the bond stress-slip relationships versus temperature.
There seems to exist some relation between the bond stress and the actual compressive strength (not discussed in detail), at least for the air-dry and the water-saturated concrete for mix 1 and the sealed concrete for mix 2, which feature can be seen in Fig. 6, represented by the ratio \( a(T)/f_{ccm}(T) \). At -40°C a mean value of 0.75 could be adopted for this ratio.

Hence the bond stress-slip curves were approximated at -40°C by the expression:

\[
\tau_b(T) = 0.75 f_{ccm}(T) \Delta^{0.48}
\]

in which the mean compressive strength \( f_{ccm}(T) \) is given by the formulae 2 and 3.

3.4 Concrete elements subjected to direct tension

To study the influence of low temperatures upon the crack width and spacing a number of experiments were performed on centrically reinforced specimens of 1000 mm in length. These specimens were subjected to direct tension at different temperatures, see Figs. 7 and 8.

![Figure 7. Mean crack width versus steel stress at the crack for different temperatures and mix 1.](image)

The load at which cracking of the member started was found to increase markedly due to the increase in tensile strength at low temperatures. Consequently, the steel stress after cracking increases also at low temperature, which feature is shown in Figs. 7 and 8. Furthermore, it was found for mix 1 that at low temperatures the crack width decreases in comparison with the crack width at room temperature for a certain stress at the crack. However, greater crack widths were observed after testing for mix 2 at -40 and -80°C respectively. It should be noted that in the latter case the number of
cracks decreases at lower temperatures. Consequently the crack width increases. It was observed that all the crack widths lay in the scatter range which usually occur at room temperature. By using Noakowski's method to predict crack spacing and width a similar tendency was found. It appeared that crack width and spacing can be calculated by using the classical concept of a unique bond stress-slip curve.

![Figure 8. Mean crack width versus steel stress at the crack for different temperatures and mix 2.](image)

However, for water-saturated concrete we have to take account of the internal prestressing of the concrete as a result of the differential thermal strain between concrete and reinforcement. This effect very greatly increases the crack spacing in saturated members at low temperatures and consequently, the crack width will be larger at low temperatures than at room temperature for a certain steel stress. However, this is the subject of further research.

4. CONCLUSIONS

Sealed and air-dry concrete exhibited almost linear thermal deformation and perfect reversibility. It turned out that changes in the moisture content have virtually no effect on the thermal deformation. Only small differences in the coefficient of expansion of the reinforcement and concrete were found.

Water-saturated concrete showed an expansion in the transition range (0 to -60°C) which was clearly influenced by the water/cement ratio and increased for higher ratios.

In general, the greater part of the increase in tensile splitting strength occurs in the temperature range from 0 to -40°C and a maximum splitting strength is found at -80°C.

An increase in bond resistance was found at lower temperatures. However, the main part of this increase occurred at temperatures down to -120°C.
Splitting failure was found to be the governing failure mechanism for water-saturated concrete with a low water/cement ratio.

The bond stress-slip relationship could be approximated by a power function.

Crack spacing and width can be calculated for sealed and air-dry concrete by using the classical concept. For the concrete with low water/cement ratio always a smaller crack width was found at lower temperatures in comparison with room temperature.

5. ACKNOWLEDGEMENT

These investigations have been carried out with the financial support of the Netherlands Technology Foundation (S.T.W. grant DCT 25.0298 to prof.dr.ir. A.S.G. Bruggeling and Prof.dr.-ing. H.W. Reinhardt), which is gratefully acknowledged.

6. REFERENCES


ICE LOADS ON PROPELLER BLADE OF SMALL CAR FERRY

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1 ABSTRACT

During the winter 87 extensive long term measurements in full scale were performed on board a small car ferry which was operating in the south-west archipelago of Finland. The normal and shear stresses on one propeller blade were measured with strain gauges by using such a configuration that the bending moments and spindle torque of the blade could be estimated with a good accuracy. From these quantities it is possible to evaluate also the components of the concentrated force, which was normal to the blade sections, and its location on the surface of the blade. The new feature in these measurements was that they lasted the whole winter period, the total effective recording time was over six hundred hours, and thus the collected data includes also information of the statistical distribution of the blade loading.

This paper introduces the main principles of the conditioning system. The given results include the examples of time domain samples of blade bending moments and spindle torques. These measured signals are also explained in such manner that the orientation and magnitude of the component of the concentrated ice load, which is perpendicular to the blade surface, can be followed over the blade. Also the development of the concentrated contact paths in the propeller plane are given during the sequence of ice impacts. The chosen samples are representative for the measuring period and area.

2 BACKGROUND

2.1 Aim of project

The aim of the work was to study the behaviour of the propulsion machinery under ice conditions and collect the statistical data from the longer time period (one winter term). There are rather many investigations of the matter concerning short terms done by both our laboratory /1/ and also some other institutions /2/. One of the detailed goals of the examination and the object of this paper was to study what happens on the propeller plane and how the blade will sustain the ice loads. The statistical behaviour of the propulsion system under ice conditions seen from the more general level are introduced in the paper Ice loads on the CP-propeller and Propeller Shaft of Small Ferry and Their Statistical Distribution During Winter '87 /3/.

The research project was initiated in co-operation with Valmet Helsinki Shipyard and fulfilled with Wärtsilä Marine after the maritime industry activities of these companies were merged.
3 SHIP

3.1 Vessel

The measurements were done on board an archipelago ferry *Gudingen*, built by Laivateollisuus Oy in Turku. Her main parameters are as follows:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length overall</td>
<td>48.5 m</td>
</tr>
<tr>
<td>Length pp.</td>
<td>42.2 m</td>
</tr>
<tr>
<td>Molded beam</td>
<td>10.5 m</td>
</tr>
<tr>
<td>Draft</td>
<td>3.75 m</td>
</tr>
<tr>
<td>Power</td>
<td>1.6 MW (MCR)</td>
</tr>
<tr>
<td>Propeller speed</td>
<td>6.35 rps (MCR)</td>
</tr>
</tbody>
</table>

![Fig.1 Side view of the ferry](image)

3.2 Shafting and propeller

The ferry had a medium speed propulsion system with one main engine, reduction gear and controllable pitch propeller. The blades and the hub of the propeller were made from aluminium bronze and they were classified in Det Norske Veritas according to the Baltic ice class 1A*. The main parameters of the propeller geometry were:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter</td>
<td>2.0 m</td>
</tr>
<tr>
<td>Hub diameter</td>
<td>0.72 m</td>
</tr>
<tr>
<td>Number of blades</td>
<td>4</td>
</tr>
<tr>
<td>Pitch ratio at 0.7R</td>
<td>0.853</td>
</tr>
<tr>
<td>Expanded blade area ratio</td>
<td>0.606</td>
</tr>
</tbody>
</table>

4 INSTRUMENTATION

4.1 Measured quantities

The following quantities were registered from the propulsion machinery and ship systems:

- blade bending moment 1
- blade bending moment 2
- blade spindle torque
- propeller shaft bending moment 1
- propeller shaft bending moment 2
- propeller shaft thrust
- propeller shaft torque
- propeller blade angle
- propeller speed
- ship speed
- main engine fuel rack position and
- rudder angle
All these quantities were measured with such conventional techniques as strain gauges and potentiometers. The ship speed was the only exception and it was got directly from the ship's own instrumentation.

4.2 Propeller blade gauging

One of the propeller blades was chosen for instrumentation and fitted with strain gauges. The gauges were located so that the bending moments of the blade round two separate cross sections and spindle torque of the blade round the blade axis could be estimated with reasonable accuracy. The bridges were located on both sides of the blade and protected with threaded covers. Location of the gauge recesses are given in Fig.2.

![Fig.2 Gauging recesses and the measured quantities on the propeller blade](image)

4.3 Shaft gauging

The torque, thrust and bending moment of the propeller shaft was measured simultaneously with the propeller blade stresses. The strain gauge bridges for bending moment were located between propeller flange and the outer stern tube bearing. They were distributed so that both the direction and the magnitude of the moment was able to determine in the fixed coordinate system of the propeller shaft.

4.4 Calibrations

The measuring system of the blade was calibrated on the yard after the blade and the propeller was assembled into the ship. Concentrated forces produced with a hydraulic cylinder were used as calibration loads. Location of point forces, given in the subsequent Fig.3., were determined in cylindric coordinates whose

![Fig.3. Calibration points on the face of the blade](image)
axis coincides with the propeller shaft. The shaft signals were calibrated with either calculations or pollard pull tests.

4.5 Signal conditioning and data collection system

The strain gauge amplifiers for blade and shaft signals were located on the propeller shaft and the data were transmitted with telemetric transducers from the rotating machinery. These and such other signals as shaft speed, ship speed, rudder angle and propeller pitch were then low pass filtered and recorded both with an instrumentation recorder and an automatic data collection system. As an exception was the shaft thrust signal which was also high pass filtered because of the zero drift caused by poorer long term stability of the measuring system with a great gain. The instrumentation tape recorder was used only as a back up device to save information at the beginning of the term when the success of the automatic data collection was not assured. The subsequent Fig.4, will show the block scheme of the computer based data gathering system. The samples of the maximum signals as a function of time was recorded during the automatic long-term measurements. In addition to these also statistical level and peak distributions were formed in real time from most of the measured quantities. This paper deals however mainly with the collected samples of propeller blade and shaft signals and the results which can be derived from those. Typical time domain samples are shown later in Figs. 7 and 9.

5 MEASUREMENTS

5.1 Time and place of measurements

This long term measurement was started at the beginning of February and ended at the end of April in the year 1987. The ferry operated most of the period between Långnäs and Kökar in the archipelago of Åland. The route of the ferry, which was either in the ship's own channel or in the channel of large passenger ferries maintaining traffic between Turku and Stockholm, is shown in Fig.5. The distance of the passage between these two places was about twenty five miles. At the end of the period the ferry continued from the Kökar island to the Galtby harbour on the isle of Korpo. This part of the route was somewhat longer than the previous one.
5.2 Ice conditions

The winter -87 was very cold, thus the ice conditions in the operating area grew severe. The curves of the temperature and the ice and snow thicknesses during the measuring term are given in Fig.6 and some values of compressive ice strength in Tab.1.

Fig.5 Route of the ferry

Fig.6 Temperature and ice and snow thicknesses in the operating area during the measuring term.
<table>
<thead>
<tr>
<th>Compression direction of the test pieces</th>
<th>Ice quality</th>
<th>No. of tests</th>
<th>Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>perpendicular to brines</td>
<td>level ice</td>
<td>2</td>
<td>2.4</td>
</tr>
<tr>
<td>parallel to brines</td>
<td>level ice</td>
<td>7</td>
<td>4.6</td>
</tr>
<tr>
<td>arbitrary to brines</td>
<td>channel ice</td>
<td>4</td>
<td>3.6</td>
</tr>
</tbody>
</table>

Tab.1 The compressive strength of ice in the operation area

6 RESULTS

6.1 Ice loads on the blade

As a typical example of great ice loads is an impacts which concentrates on the leading half of the back of the blade. The measured signals of the blade bending moments and spindle torque in such a case are shown in Fig.7.

![Fig.7 Bending moments and spindle torque of the propeller blade](image)

From the above signals it is possible to estimate as a function of time the magnitude and the location of the component of the concentrated ice load, which is affecting perpendicular to the instrumented cross section of the blade. The accuracy of the force approximation is about one grade less than the accuracy of the above given moment quantities mainly because of the complex effect of the blade geometry and the insensitivity of the measuring system to the direction of the blade sections. The estimated ice force in the time scale are given in Fig.8. The path of its' concentration point and the blade section at the radius 0.9R with the incidence path are also given in the same figure. The time difference between the path marks is 0.002 seconds.
Six different samples of ice loads are collected in Figs. 9a - f. It is characteristic for them that the big loads are more often met with a high advance speed of the ship and they are also bending the blade backwards. Fig.9e is worth of special attention because it tells about a case where the engine was overloaded. The ship is still advancing but the engine is already shutting down. The given series includes four cases where the blade is bent backwards and two where the bending direction is forward. It seems to be characteristic that the concentration path of ice loads is located on the leading edge or the leading half of the blade with the backward bending and on the middle area of the blade with the forward bending. Here it has to be mentioned that somedynamically magnified because the lowest natural frequency of the blade was about 100 Hertz. This is quite near the rising time of the impact loads for example in the above cases of Figs. 9a and 9d.
Fig. 9a  Backward bending of the blade, response signals are dynamically magnified.

Fig. 9b  Forward bending of the blade

Fig. 9c  Backward bending of the blade
Fig. 9d  Forward bending of the blade, response signals are dynamically magnified

Fig. 9e  Backward bending of the blade, engine is shutting down

Fig. 9f  Backward bending of the blade, yield strength is exceeded
Another fact is that the remarkable forward acting forces are always recorded with a rather high angle of attack of the blade sections at the impact radius of the propeller. This assumption of the meaning of hydrodynamic effects is in good accordance with the results of these and some other measurements \(4,5\). It is probable that there will be a wedge formed area between the propeller blade and the ice block where the pressure in the water is very low due to the restricted flow. This causes a force on the blade, which is affecting forwards and concentrates to the middle area of the back of the blade. Simultaneously when the angle of attack is high enough the ice crushing area near the leading edge will be reduced on the back and increased on the face of the blade. This is illustrated in Fig. 10. Because

![Diagram: Hydrodynamic effect between the ice block and the propeller blade](image)

Fig. 10 Hydrodynamic effect between the ice block and the propeller blade

Because the measuring system is designed only to give the total force approximation for the ice impact the appearance of the two separate phenomena affects considerably the estimation of the tangential location of the total force but not so much to the magnitude and the radial location of the force.

The frequency and magnitude of the occurring backward affecting ice force are pronounced when the angle of attack is decreased. The magnitude of the load correlates also to the advance speed of the ship, the higher the speed the higher the backward affecting load. Good examples of such loads are given in Figs. 7, 8 and 9f. In both these cases the absolute level of the total force is about 300 kN and the yield strength of the blade material is exceeded. This can be seen from the measured signals because they caused a sudden permanent shift of the signals' zero level. The bridges were certainly rebalanced later on.

7 CONCLUSIONS

The angle of attack of the blade section is rather sensitive to the movements of the ice block and the propeller. This can affect considerably the way the ice loads are developed.

The big ice loads are affecting backwards when the ship is going ahead. This means that the main ice pressure is against the back of the blade and where the main part of the ice block locates. These backwards affecting loads can reach the level where the yield strength of the blade material will be exceeded. This does not mean catastrophe but can be accepted and such yielding may occur rather often in practice.

The very low hydrodynamic pressure between ice and blade plays an important role in explaining the behaviour of forward acting ice loads.
The ice and fluid pressures over the blade surface seem for us the right way to model the impact phenomena. Such models can have both theoretical and empirical background.

8 REFERENCES


ABSTRACT

The ice-loading mechanism associated with ice/structure interaction in arctic environments is such that the peripheral wall of offshore structures will be subjected to lateral loads with a significant cyclic component.

This paper presents the results of a testing program undertaken to assess the effects of cyclic loading on the lateral load capacity of a composite (steel/concrete) ice-resisting wall system. The ultimate shear strength and load deformation behaviour of wall panels subject to static and cyclic lateral loads are evaluated and test results are compared with both empirical and theoretical strength equations which have been developed specifically for composite wall design.

1. INTRODUCTION

The exterior walls of offshore oil and gas production structures located in arctic waters must be designed to resist ice forces that are an order of magnitude greater than the typical environmental loads associated with offshore structures in ice free waters. Composite steel/concrete sandwich panels have been proposed as a cost effective structural system for this application. The composite system consists of two continuous steel plates enclosing a concrete core to which they are intermittently fastened by some mechanical means. Recent research has demonstrated the efficiency of composite wall panels in
transmitting large lateral forces to support bulkheads (Adams et al. 1988). Tests have shown that composite members have a high flexural and shear capacity and fail in a ductile manner, resulting in a large capacity to absorb energy.

Research to date has focused on the static lateral load capacity of composite panels. However, field studies reported by Sanderson (1988) have shown that the nature of ice loading is such that repeated crushing, pulverization and subsequent extrusion of ice at the ice/structure interface, during an interaction event, results in a loading history that possesses a significant dynamic or cyclic component. This paper reports the findings of an experimental program, undertaken as a co-operative research venture by the Centre for Frontier Engineering Research (C-FER) and the Technical Research Centre of Finland (VTT), to investigate the effects of cyclic lateral load on the ultimate strength and ductility of composite wall panels.

2. EXPERIMENTAL PROGRAM

2.1 Overview

The composite wall configuration evaluated in this study is shown in Figure 1. The structural system consists of continuous steel face plates spaced apart and intermittently tied together by transverse diaphragm plates. The interior void spaces are filled with plain concrete. Internal load transfer is achieved by interface friction and direct bearing between concrete and steel at the face-plate-to-diaphragm-plate junction.

The flexural capacity of these composite panels is primarily controlled by the tensile strength of the steel face plates, mobilized through truss action. The cyclic load capacity of welded steel plates in tension is well documented and is therefore not a concern. However, the shear capacity of these composite panels is controlled by the compressive strength of the confined struts which form in the concrete cores. The cyclic load capacity of the unreinforced concrete compression struts is not well defined and this testing program therefore focuses on the shear strength of cyclically loaded composite panels.
Figure 1. Composite Ice-Resisting Wall

2.2 Description of Tests

Load tests were carried out on three sets of matched specimens. Each set consisted of two test specimens; one specimen was loaded to failure in one cycle to serve as a control, the other specimen was loaded cyclically prior to final loading to failure. All specimens were simple span slab-type elements subjected to two concentrated line loads applied over the middle third of the span. Four specimens were tested at the Technical Research Centre of Finland (VTT series). Specimen configuration and loading arrangement are shown schematically in Figure 2. Two additional specimens, of similar configuration, were tested at the Centre for Frontier Engineering Research (CF series). Specific geometric and material properties for all test specimens are summarized in Table 1.

2.3 Load Simulation

The loading parameters for the cyclically loaded specimens in the VTT series (VTT 2 and VTT 4) were chosen to reflect the load history that might be experienced by the peripheral ice wall in an offshore structure subjected to one extreme ice load event of sustained duration. To this end the lateral load was cycled
Figure 2. Test Specimen Configuration and Loading Arrangement

Table 1. Summary of Specimen Parameters and Test Results

<table>
<thead>
<tr>
<th>Specimen</th>
<th>VTT 1</th>
<th>VTT 2</th>
<th>VTT 3</th>
<th>VTT 4</th>
<th>CF 1</th>
<th>CF 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometry:**</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>L (mm)</td>
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<td>910</td>
<td>910</td>
<td>910</td>
<td>1001</td>
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<td>b (mm)</td>
<td>600</td>
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<td>600</td>
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<td>h (mm)</td>
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<td>216</td>
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<td>216</td>
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<td>200</td>
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<td>tf (mm)</td>
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<td>8.05</td>
<td>8.05</td>
<td>8.05</td>
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<tr>
<td>tw (mm)</td>
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<td>6.08</td>
<td>6.08</td>
<td>6.08</td>
<td>6.66</td>
<td>6.66</td>
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<tr>
<td>fc (MPa)</td>
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<td>52.7</td>
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</tr>
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<td>Load History</td>
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<td>cyclic</td>
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<td>cyclic</td>
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<td>cyclic</td>
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<td>No. of Load Cycles</td>
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<td>1</td>
<td>2000</td>
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<td></td>
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<td></td>
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</tr>
<tr>
<td>Low (kN)</td>
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<td>900</td>
<td>----</td>
<td>900</td>
<td>----</td>
<td>496</td>
</tr>
<tr>
<td>High (kN)</td>
<td>----</td>
<td>1700</td>
<td>----</td>
<td>1700</td>
<td>----</td>
<td>1000</td>
</tr>
<tr>
<td>Cracking Load (kN)</td>
<td>1493</td>
<td>1438</td>
<td>1103</td>
<td>1303</td>
<td>----</td>
<td>1530</td>
</tr>
<tr>
<td>Failure Load (kN)</td>
<td>2003</td>
<td>2198</td>
<td>1869</td>
<td>1965</td>
<td>2095</td>
<td>2050</td>
</tr>
<tr>
<td>Shear Strength:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test (kN)</td>
<td>1002</td>
<td>1099</td>
<td>935</td>
<td>983</td>
<td>1048</td>
<td>1025</td>
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<tr>
<td>Predicted Emp. (kN)</td>
<td>1101</td>
<td>1101</td>
<td>1067</td>
<td>1067</td>
<td>954</td>
<td>996</td>
</tr>
<tr>
<td>Predicted UBP* (kN)</td>
<td>1059</td>
<td>1059</td>
<td>1042</td>
<td>1042</td>
<td>1011</td>
<td>1055</td>
</tr>
<tr>
<td>Strength Ratio:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test / Empirical</td>
<td>0.91</td>
<td>1.00</td>
<td>0.88</td>
<td>0.92</td>
<td>1.10</td>
<td>1.03</td>
</tr>
<tr>
<td>Test / UBP*</td>
<td>0.95</td>
<td>1.04</td>
<td>0.90</td>
<td>0.94</td>
<td>1.04</td>
<td>0.97</td>
</tr>
</tbody>
</table>

* UBP = Upper Bound Plasticity
** see Figure 2 for definition of geometric properties
between 45% and 85% of the walls assumed ultimate static load capacity for 2000 cycles. The number of load cycles applied was arrived at as follows:

\[ \text{cycles} = 1 \text{ event} \times 30 \text{ min./event} \times 60 \text{ sec./min.} \times 1 \text{ cycle/sec.} \]
\[ = 1800 \text{ round up to } 2000 \]

The load history for the cyclically loaded specimen in the CF series (CF 2) was chosen to reflect the loading history that could be experienced by the peripheral ice wall subjected to one ice load event of sufficient magnitude to cause cracking in the concrete cores, followed by frequent ice load events of moderate intensity and duration over the course of its full service life. To simulate this case, the lateral load was incrementally applied to the specimen until shear cracks formed in the concrete filled end panels. The load was subsequently reduced and then cycled between 25% and 50% of the walls assumed ultimate static capacity for approximately 200,000 cycles. The number of load cycles applied was determined as follows:

\[ \text{cycles} = 25 \text{ yr.life} \times 25 \text{ events/yr.} \times 10 \text{ min./event} \times 60 \text{ sec./min.} \times 1/2 \text{ cycles/sec.} \]
\[ = 187500 \text{ round up to } 200000 \]

It should be noted that the dynamic load parameters were chosen somewhat arbitrarily with the intention being to overestimate both the load levels and the number of load cycles that would be experienced by a real offshore structure.

2.4 Test Results

Under load all test specimens exhibited relatively linear load-deformation behaviour until significant diagonal shear cracks formed in the concrete cells adjacent to the support points. Shear cracking occurred at an average load level corresponding to two-thirds of the ultimate load capacity of the specimens. The formation of shear cracks was in most cases accompanied by a slight increase in specimen deflection. In all cases increased loading was associated with a gradual reduction in panel stiffness. Following attainment of ultimate capacity the specimens exhibited a moderate drop in strength but the reduced load carrying capacity was sustained through large member deformations. The failure mode of a representative specimen (VTT 3) is shown in Figure 3. Cracking loads, cyclic load ranges and ultimate loads

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for all specimens are summarized in Table 1. The load-deformation curve for a representative specimen subject to high amplitude, low cycle load (specimen VTT 4) is shown in Figure 4. The load deformation curve for the specimen subject to low amplitude, high cycle load (CF 2) is shown in Figure 5.

3. DISCUSSION OF TEST RESULTS
3.1 Ultimate Shear Capacity

A comparison of ultimate lateral load capacities for the statically and cyclically loaded specimens in each test series indicates that no significant shear strength reduction is associated with cyclic loading of moderate intensity and duration. Both specimens subject to high amplitude, low cycle load (VTT 2 and VTT 4) failed at approximately 107% of the static load capacity of the corresponding control specimens (VTT 1 and VTT 3). The specimen subject to low amplitude, high cycle load (CF 2) failed at 98% of the static load capacity of the control specimen (CF 1).

3.2 Creep Under Load

A study of the load deformation behaviour of the cyclically loaded specimens reveals that a limited amount of permanent creep deformation occurred during the cyclic loading phase of each test (Figure 4 and Figure 5). For the two specimens subjected to high
amplitude, low cycle load (VTT 2 and VTT 4), the maximum creep was 0.65 mm in 2000 cycles (0.33 mm per 1000 cycles). This corresponds to a 17% increase in total deflection at a mean load level of approximately two-thirds of ultimate. The specimen subjected to low amplitude, high cycle load (CF 2) exhibited a creep of 0.60 mm in 214 000 cycles (0.0028 mm per 1000 cycles) which amounts to a 21% increase in total deflection at a mean load level of approximately one-third of ultimate.

It is the opinion of the authors that the permanent creep deformation exhibited by the specimens during cyclic loading, (amounting to approximately 20% of the elastic deformation at the mean load level), constitutes an acceptable level of performance.
3.3 Ductility

The post-ultimate load carrying capacity and the amount of specimen ductility exhibited by the cyclically loaded specimen VTT 4 (Figure 4) compares favourably with the post-ultimate behaviour of the corresponding statically loaded specimen VTT 3 (not shown). In qualitative terms, the post-ultimate load-deformation behaviour of all cyclically loaded specimens tested in this program correlates well with the existing data base for statically loaded panels of similar configuration. Based on the limited test data reported herein it appears therefore, that neither post-ultimate strength nor ductility characteristics are adversely affected by cyclic loads of moderate intensity and duration.

4. PREDICTED SHEAR STRENGTHS

Existing North American design standards do not specifically address the shear strength of laterally loaded panels of composite design having an unreinforced concrete core. Recent studies have shown that existing empirical code equations significantly underestimate the shear strength of composite panels. In addition, the lower bound plasticity method, based on strut-and-tie models, which serves as an excellent method for visualizing the flow of forces and for determining reinforcement requirements, is not well suited to predicting the shear capacity of the unreinforced concrete core. In this context, an extensive testing program, involving over 40 specimens, has been carried out on a proprietary basis by the Centre for Frontier Engineering Research. This has led to the parallel development of two distinct approaches to the prediction of the ultimate shear strength of composite wall panels with unreinforced concrete cores.

4.1 Empirical Method

Adams et al. (1987) have developed an empirical best-fit shear strength equation based on a linear regression analysis of significant geometric and material parameters that were first isolated by Zsutty (1968) in his statistical analysis of the shear strength of reinforced concrete beams. The empirical shear strength equation is
\[
V_c = \frac{1.35 f_c b d \sqrt{\rho}}{(a/d)^{1.3}}
\]

where \( \rho = \) reinforcement ratio = \( t_f / d \), \( d = \) effective depth = \( h - t_f \),
\( b = \) tributary wall width, \( h = \) total wall depth, \( t_f = \) face plate thickness,
\( a = \) shear span (centre-to-centre of load points), and
\( f_c = \) uniaxial compressive strength of concrete (standard cylinder test).

The empirical equation is simple and therefore relatively easy to apply. However, empirical equations are often not valid for members which differ significantly from those for which the equations were derived; they must therefore be used with caution.

4.2 Upper Bound Plasticity Method

Adams et al. (1987) have also developed a best-fit shear strength equation based on upper bound plasticity concepts for concrete as developed by research workers at the Technical University of Denmark (Nielsen 1984). Further refinement of this method, incorporating work by Kemp and Al-Safi (1981), has led to a new formulation for the shear strength of unreinforced composite walls which is

\[
V_c = \frac{v b d f_c}{2} \left[ (1 + \lambda^2)^{1/2} - \lambda \right]
\]

for \( \omega \geq \frac{v}{4} \left\{ \lambda \left[ (1 + \lambda^2)^{1/2} - \lambda \right] + 1 \right\} \)

\[
V_c = \frac{v b d f_c}{2} \left\{ \frac{(1 + \lambda^2)^{1/2}(d^2 + r^2)^{1/2} - (d + \lambda r) + 4 \omega d}{(r + \lambda d)} \right\}
\]

for \( \omega < \frac{v}{4} \left\{ \lambda \left[ (1 + \lambda^2)^{1/2} - \lambda \right] + 1 \right\} \)

where
\[
r = d \left\{ \frac{\lambda \left[ 1 + \lambda^2 \right]}{(3\lambda^2 - 1) - A} \left[ 1 + \left( 1 - \frac{\left[ \lambda^2(3 - \lambda^2) \right] - 3\lambda^2 - A \left[ 3\lambda^2 - 1 - A \right]^{1/2}}{\lambda^2(1 + \lambda^2)^2} \right] \right] \right\},
\]
\[A = 8 \frac{\omega}{v} \left( 2\omega + \lambda^2 - 1 \right), \quad \omega = \text{mechanical reinforcement ratio} = \frac{t_f f_y}{d f_c},\]
\[
\lambda = \text{effective shear span-to-depth ratio} = \frac{a' - 2(t_f)}{h - 2(t_f)},
\]
\[
a' = \text{shear span (clear distance between load points)},
\]

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This upper bound formulation has a sound theoretical basis and provides slightly better correlation with test results, when compared with the empirical approach. In addition, the improved correlation has been found to hold over a wider range of member geometries and span-to-depth ratios.

4.3 Correlation Between Test Strength and Predicted Strength

Shear strength predictions, based on both empirical and upper bound plasticity methods, are given in Table 1 for all specimens tested in this program. Actual failure loads and ratios between test strength and predicted strength are also tabulated. It was found that the average ratio between test strength and predicted strength was 0.97 using both the empirical method and the upper bound plasticity method. The greatest discrepancy between test and predicted strength occurred with statically loaded specimen VTT 3 which yielded a test strength to predicted strength ratio of 0.88 using the empirical method and 0.90 using the upper bound plasticity method. In general results indicate that correlation between test strength and predicted strength is excellent.

5. SUMMARY

The results of a testing program of limited scope, undertaken to evaluate the effects of cyclic loading on the lateral load capacity of a composite ice-resisting wall system, indicate that neither ultimate shear strength nor post-ultimate ductility are significantly effected in an adverse way by cyclic loads of moderate intensity and duration. Permanent creep deformations resulting from sustained cyclic load were found to be significant but within acceptable levels. Shear strength prediction equations, previously formulated on the basis of test results for statically loaded composite panels with unreinforced concrete cores, yield strength predictions that are in good agreement with the test results reported herein. The reported results serve to supplement the existing data base for composite walls and further reinforce the validity of the shear strength equations presented.
6. REFERENCES


OPERATIONS IN THE ARCTIC
MARINE OPERATIONS OF A DETACHABLE PRODUCTION PLATFORM

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SWEDEN

ABSTRACT

Within the project "Offshore Oil Production in Arctic Areas" the disconnection and reconnection operations of a detachable production platform were performed. The example location is West Greenland at a water depth of 200 m. The detachable steel platform stands on a fixed, concrete subsea base, 30 m high. The platform is cylindrical with a conical base.

The ability of the steel platform to be detached from the base at all weather conditions is of paramount importance for the concept. The limitations for reconnection is also crucial. For both conditions the critical event is the hitting of the subsea base at high velocity.

The probability for hitting the subsea base was estimated from weather statistics and platform motion response calculated by a diffraction model which was corrected for the damping caused by the small clearance to the subsea base. A time simulation was also performed. At reconnection a first "hit" is inevitable. A rough estimate of stresses in the steel platform was performed for this case.

1. INTRODUCTION

The fast disconnection and subsequent reconnection of an oil production platform in an area with icebergs were studied within the project "Offshore Oil Production in Arctic Areas". The platform should be able to quickly leave its foundation if an iceberg advances towards it. The platform is a cylindrical steel platform with a conical base and stands on a concrete subsea base 30 m high. The thought location is west of Greenland at a water depth of 200 m.
2. WAVE EXCITED MOTION

The wave motion characteristics of the detachable platform at the location Holsteinsborg are presented below for different draughts during the detachment operation.

The linear first order motions were calculated by use of the WADAM program. It is included in the SESAM program package for offshore calculations developed by Sesam Systems A/S, Norway. The WADAM program includes both Morison and diffraction theory. The short term motion response was then calculated, using Pierson - Moskowitz wave spectra, for sea states of various return periods for the area around Holsteinsborg. The actual sea states are as shown below:

Table 1. Sea states west of Holsteinsborg.

<table>
<thead>
<tr>
<th>Return period</th>
<th>$T_z$ (s)</th>
<th>$H_s$ (m)</th>
<th>$H_{max}$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 years</td>
<td>9.5</td>
<td>9.50</td>
<td>16.4</td>
</tr>
<tr>
<td>10 years</td>
<td>9.1</td>
<td>8.55</td>
<td>14.8</td>
</tr>
<tr>
<td>1 year</td>
<td>8.6</td>
<td>7.63</td>
<td>13.2</td>
</tr>
<tr>
<td>1 month</td>
<td>8.1</td>
<td>6.76</td>
<td>11.7</td>
</tr>
</tbody>
</table>

The motions of the platform at the draught of 160 m (10 m clearance) for the three first return periods are shown in Table 2. The motions are very small compared to the motions of semisubmersibles.

Table 2. Significant motion responses.

<table>
<thead>
<tr>
<th>Return period</th>
<th>Significant double amplitude</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Surge/Sway (m)</td>
</tr>
<tr>
<td>100 years</td>
<td>3.3</td>
</tr>
<tr>
<td>10 years</td>
<td>2.5</td>
</tr>
<tr>
<td>1 year</td>
<td>1.7</td>
</tr>
</tbody>
</table>
The critical motion with regard to the probability of the platform hitting the bottom foundation is the vertical absolute motion at the edge of the platform base. This motion was calculated for the draught 160 m, 168 m, 169.50 m, 168.75 m, and 169.90 m. The motion for the last draught, rather close to the bottom, is afflicted with uncertainty.

The significant vertical motion of the lower edge of the platform for different sea states is shown in Table 3. This motion was used in the probability analysis, see further Section 4.3.

Table 3. Significant response motion of the platform edge.

<table>
<thead>
<tr>
<th>Draught/Clearance</th>
<th>Return period years</th>
<th>Significant wave height (m)</th>
<th>Absolute vertical motion. (m) Sign. double amplitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>160 m/10 m</td>
<td>100</td>
<td>9.50</td>
<td>0.86</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>8.55</td>
<td>0.69</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>7.63</td>
<td>0.51</td>
</tr>
<tr>
<td>168 m/2 m</td>
<td>100</td>
<td>9.50</td>
<td>0.89</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>8.55</td>
<td>0.70</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>7.63</td>
<td>0.51</td>
</tr>
<tr>
<td>169.5 m/0.5 m</td>
<td>100</td>
<td>9.50</td>
<td>0.75</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>8.55</td>
<td>0.59</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>7.63</td>
<td>0.43</td>
</tr>
<tr>
<td>169.75 m/0.25 m</td>
<td>100</td>
<td>9.50</td>
<td>0.51</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>8.55</td>
<td>0.39</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>7.63</td>
<td>0.28</td>
</tr>
<tr>
<td>169.90 m/0.10 m</td>
<td>100</td>
<td>9.50</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>8.55</td>
<td>0.16</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>7.63</td>
<td>0.10</td>
</tr>
</tbody>
</table>

3. BOTTOM INFLUENCE AT SMALL CLEARANCES

3.1 General

When the platform is floating freely or disconnected from its operating position, it will oscillate due to wave action and due to the displacement unbalance forcing the platform into a new vertical equilibrium.
The small clearance between the platform base and the bottom foundation will increase the added mass and damping of the platform as compared to a platform floating in infinitely deep water. The added masses will be correctly calculated in the diffraction calculations (WADAM) but the damping will be greater than the calculated damping, which only contains the radiation damping.

3.2 Heave damping at small clearances

The increase of the damping in the heave, roll and pitch modes are caused by both boundary-layer friction and by direct loss of kinetic energy, when water is ejected from beneath the platform at the downward motion. The latter effect is by far the greater.

When the platform is moving downwards with the velocity, \( \dot{x} \), the water between the platform base and the foundation is pressed out through the periphery with the velocity

\[
u = \dot{x} \frac{A}{2\pi Rd} = \frac{xR}{2d}, \quad \ldots \quad (1)
\]

where \( A = \pi R^2 \) is the base area
\( d \) the clearance
and \( R \) the base radius. (See Fig. 1)

In every cycle this velocity is lost at the downward motion.

Fig. 1. Elevation of platform
The kinetic energy loss can, in a time simulation, be evaluated by an ordinary drag expression with an equivalent drag acting during the whole cycle of oscillation. This gives an equivalent drag coefficient

\[ C_D = \frac{R^4}{8d^2} = \frac{R^2}{8d} \]  

... (2)

In Table 4 below the calculated equivalent drag coefficient is given for some clearances of the proposed platform.

Table 4. The equivalent drag coefficient \( C_D \) as a function of clearance \( d \).

<table>
<thead>
<tr>
<th>( d ) (m)</th>
<th>( C_D ) (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.10</td>
<td>31300</td>
</tr>
<tr>
<td>0.25</td>
<td>5000</td>
</tr>
<tr>
<td>0.5</td>
<td>1250</td>
</tr>
<tr>
<td>1</td>
<td>313</td>
</tr>
<tr>
<td>2</td>
<td>78.1</td>
</tr>
<tr>
<td>5</td>
<td>12.5</td>
</tr>
<tr>
<td>10</td>
<td>3.13</td>
</tr>
</tbody>
</table>

3.3 Added mass due to small clearance

The added mass of the platform is greatly increased when clearance between the platform and the foundation is small. This is taken into account in the diffraction theory, but in the time integration for the disconnection analysis it is of interest to estimate the vertical added mass as a function of the clearance between the platform base and the foundation.

The reason for the increased added mass is the fact that the water is accelerated sideways out and into the space between the platform base and the foundation. When this space is narrow, the velocities in the water greatly exceed the velocities caused by platform heave in infinitely deep water.

The kinetic energy for the water between the platform base and the foundation can be represented by \( a_m x^2 / 2 \), where the added mass is

\[ a_m = \rho m R^4 / (8x) \]  

... (3)
In Table 5 this estimated added mass is compared to the heave added mass from the WADAM calculations.

Table 5 Comparison of added mass according to Eq (3) with added mass from WADAM

<table>
<thead>
<tr>
<th>Clearance (m)</th>
<th>Eq (3) (10^-9 kg)</th>
<th>WADAM (10 sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.240</td>
<td>0.458</td>
</tr>
<tr>
<td>5</td>
<td>0.479</td>
<td>0.669</td>
</tr>
<tr>
<td>2</td>
<td>1.20</td>
<td>1.20</td>
</tr>
<tr>
<td>1</td>
<td>2.40</td>
<td>1.97</td>
</tr>
<tr>
<td>0.5</td>
<td>4.79</td>
<td>3.38</td>
</tr>
<tr>
<td>0.25</td>
<td>9.58</td>
<td>6.42</td>
</tr>
<tr>
<td>0.10</td>
<td>25.16</td>
<td>17.0</td>
</tr>
</tbody>
</table>

The estimated added masses are thus overestimated for clearances below 2 m and underestimated for greater clearances as compared to those calculated in the diffraction programme. The overestimation at small clearances can be caused by the fact that the platform contains a central open well, which would lower the added mass, and which is not taken into account in Eq (3). On the other hand, the diffraction calculation may not necessarily be accurate for the smaller clearances as the used discretization of the platform surface is a little too coarse for the smaller clearances.

The maximum difference in total oscillating mass is around 30%, which is permissible in the type of estimate to be done in this investigation.

4. DISCONNECTION ANALYSIS

4.1 General

When an iceberg is approaching the platform, this is supposed to be suddenly disconnected from its foundation, and due to a created displacement deficit the platform will commence a damped vertical oscillation finally attaining a clearance of 10 m, and a draught of 160 m. The platform will also be accelerated horizontally by the current and should be towed away perpendicularly to the current in order to avoid the iceberg.
Below, first, the rise of the platform from the bottom is calculated with a simple time integration scheme. Then a kind of probability that the edge of the platform base would hit the foundation is estimated. Last an example of a three-dimensional time integration in waves and currents is shown. The estimates show that the probability of hitting the foundation is small even in rough weather.

4.2 Disconnection of the platform in calm sea

A time integration of the heave oscillation of the platform in calm sea was performed using the estimates of added mass Eq (3) and drag coefficient Eq (2) given in Section 3.

In Fig 2 the heave oscillation during the first 500 s after disconnection is shown. It is seen directly that it is only during the initial part of the first quarter cycle that there is any risk of hitting the foundation due to wave excited oscillations as the maximum 100 year amplitude is smaller than one metre.

![Fig 2. The heave oscillation in calm sea after disconnection](image-url)
4.3 Risk of base-foundation impact

In a certain combination of sea state and draught, the fraction of the total time during which the base edge of the platform would be below the foundation surface can be theoretically estimated from the fact that the vertical position of the edge is normally distributed with a variance calculated from the significant absolute vertical motion in Section 2.

If the position of the edge relative to its mean vertical position is denoted \( z \) and the clearance \( d \), this part of the total time is equal to the probability

\[
P(d) = P(z + d < 0)
\]

which was evaluated for all clearance levels for which motion calculations were done in WADAM. The probability \( P(d) \) for these clearances were subsequently multiplied by the exposition time during which the platform passed the interval around each clearance. The sum of the products of probability and exposition time was thereafter divided by the time for the first quarter cycle of oscillation. The so created probability is a qualitative measure of the risk for impact on the foundation. In Table 6 the results of the calculations are shown.

**Table 6** The probability for foundation impact during the disconnection of the platform

<table>
<thead>
<tr>
<th>Recurrence of sea state (years)</th>
<th>Probability of impact (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>1</td>
</tr>
<tr>
<td>10</td>
<td>0.2</td>
</tr>
<tr>
<td>1</td>
<td>0.003</td>
</tr>
</tbody>
</table>

The weakness of the above calculation is that the platform is assumed to perform stationary random oscillations for all clearances when, in reality, it is accelerated from rest. Therefore the estimate is conservative.
4.4 Time simulation of disconnection

Preliminary simulations of the platform motion after disconnection were performed, taking the wave action and current into account.

In the performed simulations the platform edge did not touch the foundation after disconnection as would not be expected due to the low probability for such an event. In the figures below the platform motion and clearance as functions of time are plotted for a situation with waves and current.

![Diagram](image)

Fig. 3 Clearance as function of time. Waves and current.

The performed simulation is preliminary in the respect that it was necessary to use mean properties of added mass and drag damping in the modified programme. The added mass properties and wave forces from the sink-source programme with the clearance 2 m were used. This gives overestimated wave motion but a too long eigen period when oscillating at the final draught. For the drag the coefficient at the clearance 1 m was used. This will also yield conservative calculations as concerns hitting the base because the platform will rise a little slower from the bottom. The oscillations at the final draught will on the other hand be unrealistically damped.

The programme can be changed to include the varying drag coefficient and added mass according to Section 3.
5. RECONNECTION ANALYSIS

When the platform is put back on its foundation it can be rolling and heaving due to wave action and resonance phenomena. The water beneath the platform will act as a cushion and damper and therefore the resonance motions of the platform can be disregarded as such motions have a small energy content and are efficiently damped when approaching the bottom.

For lowering the platform in a vertical position in calm weather, an estimate was made, founded on the vertical velocity of the platform and the properties of the shock waves in the steel structure and the ballast. The result of this estimate demonstrates that such a vertical impact does not constitute a problem.

In Table 7 the shock compression stress in the steel structure and the ballast material is presented assuming the platform to hit the bottom with the maximum velocity during three different sea states. The calculated stresses are conservative for a vertical impact because the damping of the water beneath the platform is not taken into account, the foundation is considered completely stiff, and because maximum velocities are estimated for the clearance 0.25 m. It was checked by the impulse law that the impact force is great enough to arrest the platform within the reflection time of the shock wave.

Table 7. Estimates of shock stress amplitude for set impact velocities.

<table>
<thead>
<tr>
<th>Recurrence</th>
<th>Impact velocity (m/s)</th>
<th>Shock stress steel (MPa)</th>
<th>Shock stress ballast (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 year</td>
<td>0.17</td>
<td>6.9</td>
<td>2.6</td>
</tr>
<tr>
<td>1 month</td>
<td>0.14</td>
<td>5.7</td>
<td>2.1</td>
</tr>
<tr>
<td>1 week</td>
<td>0.12</td>
<td>4.9</td>
<td>1.8</td>
</tr>
</tbody>
</table>

If the platform is lowered slightly tilted the contact area between platform and foundation will be nil at the first contact but will thereafter grow rapidly. The allowable tilt would be decided by the amount of compression needed to create a righting moment on the platform. No estimate of this has been done as yet, but provided the platform is lowered with care under calm conditions this should not be a problem.
6. CONCLUSIONS

The performed calculations demonstrates that the detachable production platform is a feasible concept in waters with icebergs. The probability of hitting the subsea base is low at disconnection in severe seastates and the stresses at reconnection are low in moderate sea states.

7. REFERENCES

AN INVESTIGATION OF ENVIRONMENTAL CONDITIONS AND AN EVALUATION OF SUITABLE PLATFORM CONCEPTS FOR THE SOUTHERN BARENTS SEA

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ABSTRACT

As the oil industry moves into Arctic regions, the need for environmental data and suitable platform concepts becomes vital. Based on environmental research and review of existing offshore platform technology, this paper presents preliminary design criteria and suitable substructure concepts for specific sites in the Southern Barents Sea.

1. BACKGROUND AND INTRODUCTION

In order to maintain a relatively high level of field development and hydrocarbon production, Norway must make significant new oil discoveries within the next few years. Since the Southern Barents Sea and adjacent areas are the primary sources for future strategic finds, Norwegian authorities are encouraging oil exploration in these areas.

Texas Eastern Norwegian, Inc. has sponsored a study to establish preliminary environmental design criteria and evaluate substructure alternatives for oil production platforms at three specific sites in the Southern Barents Sea (Figure 1).

Based on literature surveys and consultations with reputable scientists, this paper offers proposed preliminary environmental design criteria for the subject sites. Four suitable substructure concepts, along with associated cost figures, were selected for presentation following an evaluation of existing technology and a
search through available files of Aker Engineering and Norwegian Contractors.

2. ENVIRONMENTAL CRITERIA STUDY
2.1 Introduction

Due to increasing interest in hydrocarbon exploration in the Southern Barents Sea, attempts have been made to establish environmental design criteria for three specific sites (Figure 1). Preliminary criteria are presented in the following sections based on surveys of numerous sources.

Carstens et al. (1988) reports the importance of the melting point isotherm and the atmospheric and ocean polar fronts in understanding the Barents Sea environmental conditions. A significant amount of climatic factors are related to the location of the ocean polar front, which at the surface fluctuates with winds and currents.

2.2 Ice Design Criteria

The only entirely new environmental factors to be faced in the Barents Sea, are ice features of varying character. First year ice, ice ridges and icebergs have occurrence potential at the subject sites.

The Norwegian Polar Research Institute (Vinje, 1985) has observed and published data on sea ice extension since 1966 (Figure 1). However, no extreme years appear to have occurred during this period. Ice charts from 1902 and 1966 (Vinje, 1986) show the extreme ice edge positions during those years extending south of the subject sites (Figure 1). Sea ice of varying concentration should therefore be considered design criteria. These observations indicate the shifting position of the ocean polar front, which locates the cold/warm water border line and thereby winter sea ice edge, currents, ice transports, etc.

The sea ice and ice ridge design criteria for the selected sites will be (Vinje, 1985):

- First year ice: 1-1.50 meter thick, maximum 20 meters ice floe size
- Ice ridges: Ridge height: 1 meter
                Ridge draft: 6 meters
The occurrence of icebergs, representing the largest challenge in this region, has not been mapped sufficiently. Opinions indicating no iceberg problems at the given locations are common. However, extreme observations made in 1929 (Hønsi, 1988), in 1937 (Vinje, 1985) and during the 1988 drilling season (Sangolt, 1988) indicate that sizable icebergs must be reckoned with in the Southern Barents Sea. Scientists at the Norwegian Meteorological Institute confirmed that icebergs in the several million tonnes class may have to be considered.

2.3 Current and Tide Design Criteria

The main features of the Barents Sea currents are shown in Figure 2 (Loeng, 1988). Relatively few current surveys have been made in this area;

a firm design criteria for current is therefore difficult to establish.

However, a surface current design criteria can be formulated as shown below:

- Warm currents (from south/west): 100 cm/sec
- Cold currents (from north/east): 30 cm/sec
The knowledge of tidal variations in the Barents Sea is limited (Norsk Polarinstitutt, 1988). The tidal waves are semi-diurnal and generated in the Atlantic Ocean. At the potential development sites the Mean Spring High Water and Mean Spring Low Water are approximately 20 cm above and 20 cm below Mean Sea Level respectively.

2.4 Temperature Design Criteria

Air temperature observations in the Barents Sea have been made regularly over a long period by the Norwegian Meteorological Institute and can be summarized in site specific design criteria:

- Absolute minimum temperature: \(-35^\circ C\)
- Absolute maximum temperature: \(+25^\circ C\)

Both Loeng (1988) and the Norwegian Meteorological Institute have observed and published sea temperature data (Figure 2). Accordingly, the design criteria for sea temperature are:

- Absolute minimum temperature: \(-2^\circ C\)
- Absolute maximum temperature: \(+10^\circ C\)

2.5 Wind and Wave Design Criteria

The Norwegian Meteorological Institute has made wind observations in the Barents Sea for many years. The prevailing wind direction during the winter appears to be from the north east. No such direction has been detected during the summer. Wind design criteria based on these observations are:

- Maximum 10 minute mean wind velocity: 35 m/sec
- Extreme wind velocity: 40-42 m/sec (Eide, 1983)

Wave heights in the Barents Sea are less than in areas further south on the Continental Shelf. Although wave observations in this area have not been recorded over a long period, scientists participating in this research program agree on a wave design criteria for the Barents Sea:

- Significant wave height: 13.0m ± 0.5m
- Associated period: 15-17 sec.

2.6 Ice Accretion Design Criteria

Criteria for the occurrence of sea spray ice accretion on structures have been established by Borthwick et al. (1988); air temperature of
less than -2\textdegree C and wind velocity of more than 24 knots.

Løset et al. (1988) states that the percentage frequency of days with icing rates greater than zero in January is in the range of 20-30 at the sites to be investigated. Bear Island has a similar percentage frequency for icing as the considered sites. Accordingly, proposed maximum icing rate design criteria will be equal to the quoted criteria for Bear Island:

- Maximum icing rate: 0.9 g/m\textsuperscript{2} sec
- Extreme duration of icing events producing in excess of 7 cm/24 hrs: 30 hours
- Maximum total ice load: 500 tonnes

(Norrby et al., 1985)

2.7 Geotechnical Design Criteria

The soil sediments in the Southern Barents Sea overlays older quartenary sediments (Sætem and Hamborg, 1987) and are interpreted to be of glaciogenic origin and most likely consist mainly of till. A soil composition analysis yields a silty clay with some sand, scattered fragments of gravel and pebble size. Scientists at the Continental Shelf and Petroleum Technology Research Institute state that soil sediment thicknesses at the given locations are in the range of 0 to 100 meters.

Soil samples, obtained at depths of 8 to 30 meters below the sea bed, yielded the following results:

- Composition: 35-40% clay, 30-40% silt
- Water content: 16-35%
- Plasticity index: 20%
- Liquidity index: 40-50%
- Undrained shear strength: 30-370 kN/m\textsuperscript{2}

More sampling and investigations are needed to establish final design criteria.

2.8 Polar Low Pressure Systems and Other Environmental Factors

Among the environmental challenges in the Barents Sea are the polar low pressure systems (Olje- og Energidepartamentet, 1988). The phenomena occur during the winter and comprise strong and changing winds accompanied by snow and low air temperatures.

Fog may be expected for more than 25\% of time during the period May
through July at the subject sites (Olje- og Energidepartementet, 1988). Shallow sea smoke may form near the ice edge during the winter.

The annual precipitation reaches approximately 400 mm in the Southern Barents Sea. Rain or snow may be expected at any time during the year (Olje- og Energidepartementet, 1988).

At Bear Island, located north of the potential development sites, total darkness lasts from 3 November to 5 February. The midnight sun shines from 29 March to 15 September.

3 SUBSTRUCTURE CONCEPT REVIEW
3.1 Introduction and Philosophy

Situated in waters characterized as marginal ice zones during extreme years (Figure 1), the subject sites will require development concepts suitable for a harsh Barents Sea environment. However, compared to other oil activity frontier areas in the world, the Southern Barents Sea environment is relatively moderate.

The three sites to be investigated are located in water depths of 290, 360 and 410 meters respectively. It has been assumed that the substructures to be evaluated will support large integrated topsides, with a production rate of 200,000 bpd, having an operational weight of 25,000 tonnes. A storage capacity of ten days production is required.

Leaving the design criteria for icebergs unsettled, the substructure review has included fixed, floating and compliant structures in both steel and concrete. Among the evaluated concepts, several were found suitable for Southern Barents Sea service.

Ice management must be practiced in iceberg infested waters. Several alarm zones around platforms must be identified. If large icebergs intrude these alarm zones, decisions on whether to tow away icebergs or stop production, detach and move the platform must be made. In the event that towing, thruster washing or spraying away intruding icebergs are not successful and platform move is deemed necessary, the use of compliant and fixed structures does not appear to be feasible. According to Hanson et al. (1988), icebergs of more than 5 million tonnes are very difficult to move by support vessels.

3.2 Concrete Compliant Piled Tower (Figure 3)

A compliant piled tower differs from a fixed structure by its response characteristics and from a floating structure by being bottom
A concrete compliant piled tower has been found feasible for a North Sea site at 350 meters water depth, a topside weight of 30,000 tonnes and with the exception of ice features, similar environmental conditions to the Southern Barents Sea (Hasle, 1986). Approximately 300,000 barrels of oil can be stored within the substructure. Additional subsea storage is therefore required. The soil layer needs to be close to 100 meters thick to achieve required pile penetrations.

First year ice, ice floes, ridges and growlers can be designed for. Loads caused by these features appears to be mainly of a local character. Sufficient wall thickness and strength to accommodate impact loads and steel protection against wear are proposed in the ice/structure interaction zone. To prevent structure freeze-up, a bubbler system or a movable steel sleeve concept is considered.

A compliant tower is flexible and would thereby be suitable in avoiding direct impacts from icebergs. However, the compliancy principle is globally favourable in absorbing impact loads given the iceberg mass being of a reasonable size compared to the platform mass. Hydrodynamic loads would normally be expected to be globally governing in the design of both bottom founded compliant and fixed structures for this application.

3.3 Condeep 1/8, Monotower (Figure 4)

The Condeep Monotower is a concrete gravity base, fixed structure characterized by a single, conically shaped tower surrounded at its base by a caisson of seven cylindrical cells.

The Condeep 1/8 has been considered only for the 290 meters water depth alternative. A study assessing the feasibility of using this concept for a field located at 270 meters water depth, showed the Monotower to be well suited. Functional requirements and environmental conditions used in this study were similar to those specified for the subject sites in the Southern Barents Sea, with exception of the ice design criteria. Ten days oil production can be stored within the Monotower structure.

The silty clay soil conditions found at the considered sites are suitable for the proposed skirt pile foundation concept.

The application of the Monotower is recommended for areas with fast ice or significant amounts of drifting ice. Local and global loads due to drifting or wave thrown ice have been considered and can be
designed for mainly by providing a sufficient wall thickness and strength. Growler impacts can be designed for in a similar way.

For thick sheet ice and high pressure ridges, special features such as icebreaking cones on the concrete shaft may be required. This will reduce the ice/structure interaction forces by ensuring a bending failure of the ice rather than a crushing failure. The conditions warranting such measures are, however, more extreme than the ones normally found in the Southern Barents Sea.

As for the concrete compliant tower (section 3.2), abrasion protection at the waterline will be required in waters where ice/structure interaction occurs consistently over long periods of time.

3.4 Aker PS 15, Semi-Submersible Production Facility (Figure 5)

The Aker PS family embraces a series of purpose designed floating production facilities. The PS is a six legged semi-submersible structure with a closed pontoon arrangement.

Since the Aker PS was first developed in 1983, numerous feasibility and conceptual studies have been done. Among these, several have been undertaken for fields with similar water depths and, with the exception of the ice design criteria, similar environmental conditions to the selected Southern Barents Sea sites. Based on the specified functional/operational requirements, the Aker PS 15 was found suitable. Oil storage will not be accommodated within the semi-submersible hull, a subsea storage system will therefore be required.

Among the main factors in using the Aker PS 15 in the Southern Barents Sea, is to ensure that risers and mooring lines are protected in the ice interaction zone. Riser connectors will therefore be mounted at pontoon level and risers will be hard piped through the high risk zone. Similarly, the twelve mooring lines will be protected by passing through the high risk zone either inside the columns or in heavy metal protection pipes. Local strengthening of the columns in the ice interaction zone can be done if found necessary.

A paper by Kulsvehagen (1988) shows that for somewhat more extreme ice loads, a semi-submersible rig can be efficiently strengthened. Column ice breaking cones will reduce local ice pressures and global mooring forces. A plough shaped truss fitted to the hull can handle impact loads from bergy bits and prevent ice to be trapped between the
columns. Strengthening the mooring system will obviously improve the load resistance capacity of a semi-submersible.

If the Aker PS 15 is to be operated in areas where larger icebergs threaten the installations, quick riser and mooring line disconnect devices must be provided for emergency platform detachment and move. A thruster system can facilitate this move.

In general, catenary anchored structures are well suited for absorbing impact loads given that the mooring lines are strong enough.

3.5 Production Ship (Figure 6)

Production ships are specially designed tankers with processing and power generating equipment located on the tanker deck. The ships’ anchoring system is a turret design which allows the vessel to weathervane.

A study has proved the feasibility of a production, storage and offloading ship for an oil production of 200,000 bpd and a storage of 1,500,000 barrels. Additional subsea storage must therefore be provided. With the exception of the ice conditions, the environmental criteria and water depths were comparable to those found at the subject sites in the Southern Barents Sea. This study was based on the conversion of a 280,000 tdw tanker.

Using a production ship in the Southern Barents Sea requires that mooring lines and risers, arranged in separate sectors, enter the water through the turret, at a safe distance below the ice/structure
interaction zone. Protection must, however, be provided for the propulsion system. Hull ice strengthening must be implemented for local ice loads of pressure and impact type in the ice/structure interaction zone.

For operations in more extreme conditions where consistent fast ice and ridges occur, the production ship hull can be strengthened as an icebreaker. Based on the "weathervaning" principle, the vessel will position itself facing the ice drift direction and thereby operate as a conventional icebreaker. The global operational limitation will for this case will be the strength of the mooring system. Breaking the ice by an icebreaking shaped bow section, gives favourable global forces. A bubbler system will be considered against freeze-up. If an icebreaking hull is found necessary, a purpose-built vessel will obviously be attractive.

In areas of large icebergs, a production ship must, similarly to the Aker PS, be able to quickly disconnect for emergency moves.

A floating production system, ship or semi-submersible, should in principle have a strong mooring arrangement and be sufficiently flexible to avoid direct impacts from larger ice features (Sangolt, 1988). In general, a smaller production ship without oil storage would therefore be preferable.

3.6 Cost Comparison

A preliminary cost evaluation of the concepts covered by the studies referred to in sections 3.2 through 3.5 is shown in Table 1.

Table 1 Installed substructure costs, including required oil storage.

<table>
<thead>
<tr>
<th>Concept</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete Compliant Piled Tower</td>
<td>2199 *</td>
</tr>
<tr>
<td>Condeep 1/8, Monotower</td>
<td>2146 *</td>
</tr>
<tr>
<td>Aker PS 15</td>
<td>1490 *</td>
</tr>
<tr>
<td>Production Ship</td>
<td>1617 *</td>
</tr>
</tbody>
</table>

* No costs for modifications due to ice conditions are included
4. CONCLUSIONS

The most significant findings in this paper are the following:

- Precluding the ice conditions, the proposed environmental design criteria are not unlike the ones found further south on the Continental Shelf.

- In order to establish firm environmental design criteria for sites in the Southern Barents Sea, more observations need to be made. In particular, iceberg observations and tracking are insufficient; however, lack of environmental data completeness, in general, is experienced.

- Unless large icebergs pose a threat to the subject sites, substructures need not be vastly different from North Sea and Haltenbanken deep water concepts. Relatively minor modifications suffice.

- Of the presented substructures, the floating ones appear to be most cost efficient. However, a total feasibility study, including other effects such as topside and loading facilities, must be undertaken in order to draw conclusions on development economy.

5. REFERENCES


ADVANCES IN NONLINEAR ANALYSIS METHODS FOR OCEAN STRUCTURES USING PARALLEL COMPUTERS

Robert E. Fulton
Kuo-Ning Chiang
Dietmar Goehlich

ABSTRACT

The design of complex ocean engineering systems such as advanced ship structures and off shore platforms requires continually increased levels of detail in supporting analyses. Such design activities require large order finite element and/or finite difference models and excessive computation demands in both calculation speed and information management. Recent advances in parallel supercomputer technology provide the opportunity to upgrade current structural analysis capabilities. Most existing major structural analysis software systems were designed ten to twenty years ago and have been optimized for current sequential computers. Such systems often are not well structured to take maximum advantage of the recent and continuing revolution in parallel vector computing capabilities. These parallel vector computer architectures are not only occurring in the form of large supercomputers, but also are now occurring for minicomputers and even engineering workstations. This paper discusses some recent advances in solving nonlinear structural dynamic problems relevant to ocean engineering applications. In particular the paper reports on the development and implementation of parallel processing software for finite element solutions to ocean engineering problems. It was shown that a parallel processing approach can significantly reduce execution time for large scale finite element problems typical of ocean engineering applications.

1. INTRODUCTION

Today the finite element method is used extensively in the solution to many ocean engineering problems. For detailed analyses of complex designs, structural models composed of thousands of degrees of freedom are no longer uncommon. Parallel computers offer the promise for solution to complex problems in detail considered too time-consuming for today's sequential processors [Noor]. To benefit from advances in parallel computers, methods are needed which take maximum advantage of parallel processing features. Criteria that influence the efficiency of a parallel method include the amount of computation versus the number of processors, the communication paths and synchronization delays, and the size of a problem in relation to the number of processors used.

Finite element analysis and optimization of ocean structures subjected to static or dynamic forces typically require the solution of large systems of linear equations. Many commercial finite element codes

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[MSC/Nastran Manual, Bathe, 1975; Fredriksson and Mackerle, 1983] solve the large scale global equilibrium equations through a triangular decomposition of the system matrix in combination with a forward/backward substitution. The decomposition of the system matrix may contribute significantly to the computing cost. For example in a static stress analysis it may take more than 50% of the total computing time [Komzsik, 1986]. Recently the parallel matrix decomposition has been investigated by several researchers (eg [Chen and Dongarra, 1984; George, Heath and Liu, 1985; Heath, 1985]) but the proposed solutions have not been investigated in the environment of a practical analysis capability of a multi-purpose finite element code. One focal point of the present investigation is to investigate how complex analysis capability can be enhanced through incorporation of these parallel concepts into a production finite element system.

2. APPLICATION TO AN FEM STATIC STRESS ANALYSIS

The static solution in structural finite element analysis consists of the calculation of load vectors, the generation of the stiffness matrix of the model and the calculation of the displacement and stress state due to the applied loads. For example, in MSC/NASTRAN the following major operations are performed:

- Geometry processing
- Matrix generation and assembly
- Constraint elimination
- Solution phase 1 (matrix decomposition)
- Solution phase 2 (forward-backward substitution)
- Data recovery.

For large structural models, for which high speed computing is most desirable, the matrix decomposition is most time consuming. It may typically take more than 50% of the total execution time.

To test the performance improvement of the static analysis provided by parallel processing, several sets of benchmark problems were used. One series was built from a simple elastic plate model shown in Figure 1 using MSC/NASTRAN QUAD4 elements. By varying the mesh density a series of tasks are generated ranging from 515 to 18,015 degrees of freedom.

![Parallel Static FEM Solution: Plate Bending Test Problem, Problem Size and Matrix Bandwidth.](image-url)

Figure 1.
The benchmarks were run on CRAY X-MP and IBM 3090 computers using up to four processors. Several problem sets were run on either machine and extensive performance data has been gathered. The complete timing measurements may be found in [Goehlich, Komzsik, Fulton, 1987], here the most important results are summarized. Figure 2 shows the measured solution times $T_1$ and $T_4$ for the plate problem on CRAY X-MP. For the large models the solution time could be cut in half by using four processors ($s = 1.7$). The practical speedup stays remarkably close to the theoretical speedup (see Figure 2) which indicates excellent multi-processing performance.

3. APPLICATION TO NONLINEAR DYNAMIC ANALYSIS

The parallel methods have been incorporated in a nonlinear finite element program and applied to the analysis of a structure subjected to crash type loading conditions. The finite element system used is FENRIS, a large scale, general purpose program for nonlinear finite element analysis. FENRIS was developed as a project between the Norwegian Institute of Technology (NTH), the Society for Industrial and Technical Research (SINTEF) and the Norwegian VERITAS. Modification to FENRIS included implementation on a parallel operating system and replacement of selected sequential code by parallel code. The resulting parallel system denoted FENRIS parallel version one (FENRIS/P1, Figure 3) with a parallel LD$^{-1}$LT has been developed and installed on FLEX/32 MMOS (Multitasking Multicomputing Operating System) at Georgia Tech CAD/CAE. Laboratory. Speedups of the LD$^{-1}$LT decomposition (compare with the sequential FENRIS LD$^{-1}$LT decomposition) are very encouraging. The improvements are achieved by refined parallel computation strategies, and a machine independent waiting control routines used to reduce waiting time in the matrix decomposition.
FENRIS/P1 was applied to s-shaped box beam test problem shown at Figure 4 [20][21], subjected to impact. This finite element model comprises 180 triangular shell elements with 450 degrees-of-freedom, the maximum half-bandwidth equal to 42. Typical results showing the improved computation speedups are given in Figure 5. The results show computation speedups for the $L D^{-1} L^T$ of up to 6.32 for seven processors and indicate that the significant speedups can be achieved through the use of many processors for an appropriate finite element problem. It should be noted that the Cholesky decomposition is also well-suited for vector computation (Figure 6 and [Fulton, Chiang, 1988]. In the parallel Cholesky decomposition, each processor is responsible for decomposing the whole column of the system matrix; therefore no vector length penalty is introduced. Figure 7 shows the correlation between experimental results and the parallel computation strategies.
Figure 5. Parallel Decomposition Speedups for Test Problem.

Figure 6. Vector Speedups for Matrix Decomposition.

Figure 7. Force - Deflection During Impact.
As a second example consider the thin shell cylinder impact test problem (Figure 8). This finite element model comprises 200 quadrilateral shell elements with (1140) D.O.F. The impact phenomenon was computed on the basis of elastic-perfectly plastic constitutive material (A-36 Steel). Dynamic computations were performed via a matrix solution of Newmark's unconditional stable scheme ($\alpha = 0.5, \beta = 0.25$), with a time increment equaled to 0.0001 second. A fine mesh was not used because the limitation of CPU time and disk space on the VAX/VMS and FLEX/32. Typical results at the impact point are shown as Figure 9. The computation times attributed to CPU for the thin shell cylinder impact test problem are shown at Figure 10. This figure illustrates that the percentage of computation associated with effective stiffness matrix, internal and external force vector generation is 60.7% whereas for equation solving is 39%. In this model most of the CPU are spend on effective stiffness, nonlinear force vectors generation and equation solving. The left-hand side matrix skyline profile and typical results showing the improved computation speedups are given in Figure 11 and 12. The results show computation speedup for LD$^{-1}$LT of up to 6.44 for seven processors. From the above observations, the LD$^{-1}$LT
Figure 10. 1140 D.O.F. Thin Shell Cylinder CPU Distribution.

Figure 11. Thin Shell Cylinder Ckyline Profile.
algorithm shows good promise for parallel/vector computation and indicates that a Cholesky based finite element system such as FENRIS appears well suited for parallel/vector implementations.

4. CONCLUDING REMARKS

A study has been conducted evaluating the potential of improving the capabilities for linear and nonlinear finite element analyses of ocean structures by using parallel computers. Numerical methods typically used in FEM systems have been investigated on test problems with a view toward computationally intensive steps such as matrix decomposition and how these steps lend themselves to parallelism. The results indicate that these key computation steps can benefit significantly from parallel computing. They also indicate that there are minimum thresholds in computation tasks for multiple processors to be effective. Below these thresholds data communication becomes a bottleneck and parallel computation efficiency significantly deteriorates. The results suggest that good computational efficiency can be obtained for problems with a large number of degrees of freedom with and a moderate number of processors. It could be shown that a significant improvement in analysis capability for ocean structures can be obtained by incorporating parallel code in major finite element production codes such as a FENRIS and MSC/NASTRAN.

5. ACKNOWLEDGEMENTS

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6. REFERENCES


A. George, M. T. Heath and J. Liu, "Parallel Cholesky Factorization on a Shared-Memory Multiprocessor", Tech. Rept. ORNL-6124, March 1985, Oak Ridge National Laboratory.


**MSC/Nastran Application Manual**, MacNeal-Schwendler Corp., Los Angeles, CA.


The design premises for the conceptual development of platform systems along the west coast of Greenland has been described. Three different concepts: Floating Production Systems, Rock Islands and Detachable Platforms together with their offloading systems have been identified as technically feasible. For intermediate water depths, the detachable platform seems most beneficial and a preliminary economic evaluation demonstrates a promising economy for oil prices as low as 20 US $ a barrel.

1. INTRODUCTION

Being Danes, with a close relationship to Greenland, it is natural to consider the problems of oil production in Greenland and other similar arctic areas. A particular challenge is to develop cost effective production systems in areas which cannot be exploited with conventional platforms. The area under consideration in this study has been the west coast of Greenland, characterized by having generally open water, but with a flow of very large icebergs. The icebergs are so large that conventional platforms cannot sustain an impact and the iceberg load is therefore the dominant environmental load.

The particular area has been chosen because it is feasible with present technology to explore the area, e.g. by drilling in the summer time. Areas where the depths and ice conditions make exploration impossible with present technology, e.g. along the east coast of Greenland, will not represent realistic goals in the immediate future.
2. EVALUATION OF DESIGN PREMISES

2.1 General

Design assumptions have been established for two sites: Holsteinsborg, 120 km west of the town of Holsteinsborg, (Sisimiut), and Sukkertoppen, 70 km west of the town of Sukkertoppen (Maniitsoq), Fig. 1. The water depth of the former site is 200 m while it is 81 m for the latter. Both areas are characterized by having generally open water, but with icebergs. Only occasionally, the packice from the Disko Bay will drift south to cover the sites.

2.2 Waves, Wind & Current

The wave climate is milder than in the North Sea with 50 year wave heights of 15.9 m for Holsteinsborg and 16.2 m for Sukkertoppen.

As regards operational conditions, the significant wave height $H_s$ is less than 2 m 70% of the time at Holsteinsborg and 60% of the time at Sukkertoppen.

Wind and current velocities do not differ much from standard North Sea conditions and will not be dealt with further.

2.3 Soils

A typical soil profile on the West Greenland continental shelf consisting of moraine and tertiary sediments with properties according to Tab. 1 has been assumed.

<table>
<thead>
<tr>
<th>Depth below Sea Floor (m)</th>
<th>Type</th>
<th>$\gamma$ (kN/m$^3$)</th>
<th>$c_u$ (kN/m$^2$)</th>
<th>$\phi_{tr}$ (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-2</td>
<td>Mud</td>
<td>4</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2-22</td>
<td>Moraine</td>
<td>8</td>
<td>0</td>
<td>31</td>
</tr>
<tr>
<td>22-</td>
<td>Clay</td>
<td>9</td>
<td>90</td>
<td>0</td>
</tr>
</tbody>
</table>

2.4 Ice Cover

The ice off the west coast of Greenland consists of first year ice. Normally, it has reached its maximum extent at the end of March, where the ice covers nearly all the Davis Strait and the Baffin Bay. In late summer, both
areas are free of ice. The following values for the extreme ice condition have been assumed:

<table>
<thead>
<tr>
<th>Location</th>
<th>Ice Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Holsteinsborg</td>
<td>1.0 m first year ice</td>
</tr>
<tr>
<td>Sukkertoppen</td>
<td>0.5 m first year ice</td>
</tr>
<tr>
<td>Crushing strength</td>
<td>3.8 MPa</td>
</tr>
</tbody>
</table>

2.5 Icebergs

Icebergs are produced from glaciers along the coast of Greenland. The large icebergs are produced along the entire length of the east coast and at some locations along the west coast such as the Disko Bay and the Umanak Bay, Fig. 2.

The drift of the icebergs is influenced by winds and in particular by currents. Therefore, icebergs produced at the east coast drift southwards along the coast, around Kap Farvel and northwards along the west coast of Greenland. Icebergs produced in the Disko Bay at the west coast will drift to the southwest or follow an anti clock-wise current circulation northwards to the Baffin Bay and eventually drift southwards along the Canadian east coast.

2.6 Design Philosophy

Based on information about iceberg density, mass, draft and drift velocities, Refs. 1 and 2, a statistical model for the kinetic energy in the drifting icebergs has been developed. The probability of a collision between the platform and an iceberg has been determined and especially the probability of a collision with icebergs approaching with a kinetic energy which may be critical for the platform. The platform can only sustain iceberg collisions with kinetic energies below a certain level, for higher energies it is disconnected and removed when an iceberg is within a critical distance, Refs. 3 and 4.

An assumption for these calculations has been that the data for icebergs collected during the summer period are valid for the winter period too. For a conceptual study, this is considered acceptable. However, in case of an actual project, more comprehensive data will have to be collected.
3. CONCEPT EVALUATION

The present study has been limited to 3 different types of structures:

- Floating Production Systems;
- Rock Islands;
- Detachable Platforms.

3.1 Floating Production Systems

The choice of floating production systems seems obvious in deep waters not confined in ice all year round. The systems are well proven and can be reinforced to sustain the first year ice. However, when dealing with icebergs, special problems arise. It will not be feasible to design the structure to withstand large iceberg loads, thus the structure has to be emergency removed during the passing of the largest icebergs.

The main problem areas are the conductors and the anchor lines.

The concept presented in this project, Fig. 3 is based on a continuous production of oil during the passing of icebergs, by means of flexible risers. The deeper the water, the more feasible the floating production system, because the radius of manoeuvrability increases.

3.2 Rock Islands

In shallow waters a rock island is an attractive alternative, capable of withstanding the largest icebergs. Rock islands can be built relatively cheap, but the problem is the long construction time for increasing water depths. Our conclusion is, surprisingly, that for water depths up to nearly 100 m, the concept, Fig. 4, may be competitive, depending on the distance to rock materials.

3.3 Detachable Platforms

Between the two extremes, floating production systems and rock islands, platforms which are designed to be regularly removed during passing of the iceberg seem to be even more beneficial.

The system consists of a detachable upper part and a permanent subsea base, Fig. 5. The upper part, the hull, is a steel structure holding all production and service facilities. Locally, the platform has been designed to resist small icebergs, in order to keep the detachments at a low level.
It has been a design premise to maintain the oil production as long as possible, hence a quick release system for the hull has been developed. The system is based on a simple suction principle, enabling the detachment to take place as a last minute operation. The subsea base is built in concrete and serves as foundation for the hull. Further, it comprises the well system with the subsea Christmas trees. The base is surrounded by a subsea breakwater, which protects against impact of icebergs.

4. OIL TRANSPORTATION
4.1 Loading

The loading system is the same for all three types of developments considered. The crude oil is pumped from a storage tank via a flexible hose to the tanker. The hose can either be floated from the platform to the tanker when there is no surface ice, or it can be suspended above the water supported by a cradle extended from one of the platform service cranes.

4.2 Tanker Routing

The distance to the nearest available refinery from the platform location is a major consideration when equating the ultimate tanker size and turn around time.

It is proposed that two tankers work a rotation to and from the platform location delivering the crude to Saint Johns, New Brunswick or Glasgow, U.K.

5. ECONOMIC EVALUATION
5.1 General

A preliminary economic evaluation has so far only been made for the detachable platform concept. Based on assumptions concerning the future oil production, cost estimates and future oil prices, inflation, exchange rates and taxes, the net present value is calculated.

5.2 Cost Estimates

The following costs were used in the evaluation of the economic feasibility:
Tab. 2 Construction costs of base and platform

<table>
<thead>
<tr>
<th>COST</th>
<th>Base mio. DKK</th>
<th>Hull &amp; Deck mio. DKK</th>
<th>Total mio. DKK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete</td>
<td>3,440</td>
<td>-</td>
<td>3,440</td>
</tr>
<tr>
<td>Steel</td>
<td>315</td>
<td>3,500</td>
<td>3,815</td>
</tr>
<tr>
<td>Ballast</td>
<td>69</td>
<td>73</td>
<td>142</td>
</tr>
<tr>
<td>Mechanical equip.</td>
<td>20</td>
<td>-</td>
<td>20</td>
</tr>
<tr>
<td>Process equip.</td>
<td></td>
<td>10,000</td>
<td>10,000</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>3,844</strong></td>
<td><strong>13,573</strong></td>
<td><strong>17,417</strong></td>
</tr>
</tbody>
</table>

Base Protection 360 mio. DKK
Transportation and Installation Tugs 40 mio. DKK

Tab. 3 Investment cost per year mio. DKK

<table>
<thead>
<tr>
<th>Year</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4,715</td>
</tr>
<tr>
<td>2</td>
<td>4,354</td>
</tr>
<tr>
<td>3</td>
<td>4,354</td>
</tr>
<tr>
<td>4</td>
<td>4,394</td>
</tr>
</tbody>
</table>

Abandonment costs are assumed to be negligible.

Tab. 4 Operation costs

<table>
<thead>
<tr>
<th>Mio. DKK</th>
<th>0-4 years</th>
<th>Rest of production period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manpower</td>
<td>650</td>
<td>260</td>
</tr>
<tr>
<td>Equipment cost</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>1 ice breaker</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>4 tugs/supply vessels</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>910</strong></td>
<td><strong>520</strong></td>
</tr>
</tbody>
</table>

**Yearly Transportation Costs**

Rental of four 50,000 tons tankers at 10,000 dollars/day: 102 mio. DKK.
Downtime

Average yearly downtime due to false alarms, disconnections, maintenance and system failures is estimated at 32 days/year.

5.3 Production

The production profile, Tab. 5, is based on 26 production wells each having a peak production of 6500 bbls per day after allowing for downtime. The 26 wells are assumed drilled and put into production during the first 3½ years.

Tab. 5 Production profile

<table>
<thead>
<tr>
<th>Year</th>
<th>One well mio. bbls/year</th>
<th>Total production mio. bbls/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2,4</td>
<td>10,7</td>
</tr>
<tr>
<td>2</td>
<td>2,4</td>
<td>26,1</td>
</tr>
<tr>
<td>3</td>
<td>2,4</td>
<td>45,1</td>
</tr>
<tr>
<td>4</td>
<td>2,4</td>
<td>60,5</td>
</tr>
<tr>
<td>5</td>
<td>2,4</td>
<td>61,7</td>
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Economic Assumptions

Oil price: 35$/bbl
US$ exchange rate: 7 DKK/$
Inflation: 3% p.a.
Financing: 100% equity
Real discount rate: 6% p.a.
Calculations are in fixed 1988 prices.
5.4 Taxation

For this illustration and evaluation purpose, the present Danish royalty and tax regime is used. The system consists of a 50% corporation tax and a 70% hydrocarbon tax.

5.5 Results

The net present value of the field was calculated, and in addition, a sensitivity analysis considering changes in the oil price, production volume and costs was carried out, Tab. 6.

Tab. 6 Net present values in billion DKK (fixed 1988 DKK)

<table>
<thead>
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<td>Oil Price</td>
<td>Production</td>
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<td>NPV before tax</td>
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<td>NPV after tax</td>
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<tr>
<td>Pay out year</td>
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The project seems highly profitable with a net present value of 22 billion DKK and an internal real rate of return of 21%, provided the oil price is as high as 35 US $ a barrel.

The sensitivity analysis shows a good robustness with respect to cost overruns, lower oil prices and reduced production. However, it is estimated that the crude price shall have a level of around US $ 20 per barrel before the internal rate of return is acceptable.

6. ACKNOWLEDGMENT

The authors gratefully acknowledge the permission to publish the results from the group of companies participating in the project. The companies are
Rambøll & Hannemann (Project Coordinator), LICengineering, Danyard, ISVA/DIH, Nunaoil all from Denmark, Götaaverken Arendal AB from Sweden, SINTEF and Bjarne Instanes from Norway. The project work is supervised by an Advisory Committee holding members from BP Exploration Ltd., Statoil, D.O.N.G., the Danish Energy Agency, Grønlunds Energiforsyning and GTO.

The project is partly supported by Nordisk Industrifond, Teknologirådet, Denmark, STU and SIND, Sweden, and partly by the participating companies.

The environmental data have kindly been supplied by the Greenland Technical Organization (GTO).

REFERENCES


Vol. 1 Summary
Vol. 2 Wind and Waves
Vol. 3 Currents
Vol. 4 Icebergs


Fig. 1 Study area, Sukkertoppen and Holsteinsborg

Fig. 2 Iceberg production and current circulation
Fig. 3 Floating production system

Fig. 4 Rock island
Fig. 5 Detachable platform
ABSTRACT

Methods used and information obtained from underwater (ice) observations of ice/structure interactions of small-craft harbors in western Lake Superior are presented. The design of a marina or small-craft harbor is site-specific, and the designer must attempt to characterize each site by its relevant parameters. Included among these parameters are water motions and various ice conditions and formations. Although these parameters and harsh winter weather cause significant structure damage in Great Lakes marinas, engineers can predict relevant criteria for design at a given site. Ice conditions are being filmed and videotaped, both above and below the water surface. The ice characteristically is non-uniform and is irregular in the vicinity of structures. It may consist of rubble pieces, thick attachments, open water, or irregular lenses, shelves and cavities. Compressed air deicing results in concavities or holes through the ice sheets and smooth irregular formations, such as ice stalactites growing down into the water. Rocks on the bottom may cause scalloping on the underside of ice sheets, whereas smooth gravel bottoms are overlain by smooth ice sheets. Foam-filled polyethylene pontoons are insulators and ice forms only part way down and around their sides, but not across their bottoms. Additional work beneath the ice is planned to gain fuller understandings of the interactions of ice and structures in small-craft harbors.
1. INTRODUCTION

Wortley (1988) describes winter conditions in Great Lakes small-craft harbors in a POAC 87 conference paper. The design of a marina or small-craft harbor is site-specific, and the designer must attempt to characterize each site by its relevant parameters. These include, but are not limited to, geology, climate, lake levels, wind set-ups, seiches (defined below), currents, water temperatures, ice conditions, and general site features.

Water surface elevations of the Great Lakes vary irregularly from year to year, reaching lower levels in the winter and higher levels in the summer. Recently, levels in the Great Lakes have reached or exceeded record highs, winter and summer.

Seiches occur in addition to seasonal changes in water levels. A seiche is started by high winds and barometric pressure gradients, acting as external forces, deforming the water surface. When the forces are removed, the water mass dissipates the potential energy of the deformed surface by damped oscillation. The deformation of the water surface is known as a storm surge or wind tide; the subsequent oscillation is called a seiche. Seiche periods range between minutes and hours, with water level changes of tens of millimeters to a meter or more.

Seiches occur in all Great Lakes harbors. When ice is present, large up and down forces can be exerted on structures. Figure 1 shows damage to a fixed dock. The lake level has dropped. A rubber tire dock fender, hung from the dock with strong polypropylene ropes and frozen into the ice sheet, has literally pulled the deck down and around the steel pipe pile, punching it through the plywood deck surface. Figure 2 shows an ice collar and ice rubble pieces broken from the top of an ice sheet and frozen to a pile-supported dock. This action occurs where seiches are strong and water levels drop. Subsequent rises of the sheet, and sometimes a resultant pulling of the pile from the harbor bottom, may cause damage to the dock and to framing members.

Floating docks can be damaged by ice. Figure 3 shows a common damage problem to floating docks that are restrained in rising and falling ice. The ice has lifted, or jacked, the spuds (pipes or rods dropped to, or tapped into, harbor bottom sediments), which have become wedged in the retainers at the end of the pier. When the ice falls, the result is a breaking of the pier and its connection to the head pier.
Ice further damages floating docks, since ice sheets freeze to shorelines. Bending stresses in the ice, brought on by water level fluctuations, cause cracking parallel to the shorelines near where the ice is shorefast. In these nearshore areas, floating docks become "drawn-down" into the ice sheet due to water that rises through the cracks, thus flooding the area and then freezing. The docks become surrounded by ice, from above as well as below, and frequently twist and break. Figure 4 shows shoreline flooding and dock submergence.

Figure 1. Fixed dock damaged by ice pulling deck surface down around pile.

Figure 2. Ice collar and rubble pieces around a fixed dock pile that ice sheet has pulled.

Figure 3. Floating dock damaged by ice sheet lifting spuds that are restrained by end of pier.

Figure 4. Floating dock submerged by shoreline flooding.
Ice moves vertically as a result of water level changes and laterally as a result of a number of causes. Thermal forces cause ice to expand and contract. Natural currents or currents caused by sudden sharp seiches move ice laterally. Such seiches can change the water level one-half meter in a matter of an hour or so. Subsequently, the water that drains into or out of a harbor produces the currents. Once cracked or melted free from shorelines, ice shifts around. Finally, wind forces can move ice and pile it up in a harbor or blow it out of a harbor. Wind can also glaze or ice docks. If prolonged, the docks can become twisted or capsized.

Winter weather in Great Lakes harbors, though often harsh, causes predictable conditions. After many winters (since 1976) of observations of ice conditions in small-craft harbors, including still photography, videotaping, and time-lapse filming of ice actions, the authors have begun underwater (ice) inspections and videotaping. Marinas in western Lake Superior, which experience significant seiche action, have been observed during the winters of 1985-86 to 1988-89. The marina structures include floating docks and fixed docks, bottom-resting bin wall and crib breakwaters and piers, and compressed air deiced piles. Ice pressure ridges have also been observed and filmed.

In addition to the scuba equipment, preparations and operations described in the following section, the reader may wish to refer to Somers (1986) for more information about under ice diving equipment, procedures and cautions, including dealing with ice emergencies, cold stress, and cold injuries.

2. UNDER ICE INSPECTION PROCEDURES AND EQUIPMENT

This section presents information on the videotaping equipment and use, planning under ice dives, the equipment and personnel required, and the necessary operational and safety procedures. Figures 5 and 6 show an ice hole and ice scuba divers.

2.1 Videotaping system and use

Prior to operating the videotape system, field personnel are required to come to the University campus for a briefing and training session. The system, valued at more than $20,000, can be easily damaged if mishandled. The system consists of a black and white Osprey SIT (silicon intensified target) camera, a Cyclops control unit, and a Panasonic video recorder.
Figure 5. Ice hole for dive. Figure 6. Ice scuba divers.

Minimum temperatures of operation are: camera at \(-7^\circ C (20^\circ F)\), control unit at \(-7^\circ C (20^\circ F)\), and video recorder at \(0^\circ C (32^\circ F)\). These limitations are met by operating the recorder and control unit in a warm van truck and by running one of two camera cables, 30 and 91 meters (100 and 300 feet) long, to a hole in the ice where the divers enter the water. The camera is allowed to come to its ambient operating temperature in the ice water before it is turned on. The lens cover can then be removed. The camera operates in natural light.

The camera can be operated under the ice in daylight when the weather is cloudy, or before 10:00 a.m. and after 2:00 p.m. when the weather is sunny. Aiming the camera upwards towards a bright-backlit ice cover or ice rubble, which may focus sunlight like a prism towards the camera, will seriously damage the camera's iris.

The camera is equipped with a spot filter on the lens. With this spot filter, the camera light sensor will partially close the iris in bright light conditions. When the filter area dominates the residual iris opening, the camera will operate under light conditions that would otherwise close the iris completely.

In addition to the videotaping system, a conventional 35 mm camera, with waterproof housing and strobe for underwater still photographs, is occasionally used.
2.2 Organizing and planning an ice dive operation

The divers must be familiar with the marinas in which they dive. Pre-ice dives before winter are recommended for this familiarization. During the pre-ice dives, the areas of concern are identified and inspected. The divers can also locate and remove any obstructions on which the tether lines and videotaping cables may become entwined. Using the information obtained in the pre-ice dives, the location of the ice holes can be determined to maximize the use of the divers' limited time under the ice.

Due to the limitations on the videotaping equipment, the dives are conducted before 10:00 a.m. or after 2:00 p.m. The morning dives are scheduled as early as possible so that the dive can be completed during the usually calmer winds. The afternoon dives are conducted near sunset for the same reason.

Prior to the pre-ice and ice dives, permission must be obtained from the owner or person responsible for the operation and the safety of the marina. Usually, the marina operators are pleased to have the research conducted and have many questions about the study and problems they have with ice damages. Information obtained from the owner/operator may help determine the location of the dive. Permission to use the showers should also be obtained. The divers must have warm accommodations upon leaving the water.

For the morning dives, the hole is cut the previous day. The hole is cut on the same day for an afternoon dive. The hole should be triangular in plan shape and approximately 2 meters (6 feet) on each side. A triangular hole is easier for the divers to climb in and out of. The hole must be marked with safety cones and barricades to be visible to snowmobilers and ice fishermen. The hole can be cut using power saws with 750-mm (30-inch) bars or hand ice saws. The large ice blocks should be removed from the hole and not pushed under the sheet. If pushed under, they may become entwined with the lifeline and cables. Care must be taken to keep oil and gas from power equipment from entering the ice hole. Oil and gas will clog or foul the divers' equipment. All ice slush must be removed from the hole prior to the dive.

2.3 Additional equipment and personnel required for under ice diving

Two divers must be used on all ice dives involving video camera work. The lead diver carries the camera and does the filming. The second diver controls the lifelines, helps in orientation and is used for scaling and demonstration purposes. The divers are securely tied to the lifeline which, when using the videotaping equipment, can be the camera cable.
However, the size, weight and lack of flexibility make the camera cable hard to handle underwater; pulling on the cable for signaling is unsure and difficult.

Somers (1986) reports that many public safety dive teams deploy only a single diver under the ice at a time. This procedure is gaining popularity and is considered "safe" by many authorities. A unique diver communications system has been introduced recently that makes the single diver technique significantly safer. This system includes a combination safety/communications line, a diver-to-tender electronic communications unit, and a diver's tranducer or bone-oscillating ear-piece/microphone. The authors are not using this single-diver system for these under-ice studies.

Ideally, a three person crew should be stationed above the ice. All should be trained in scuba diving and one should be fully suited and ready to enter the water in an emergency situation.

One person is responsible for operating the Cyclops Control unit and directing and monitoring the progress of the divers. This person must be familiar with the harbor and the objectives of the dive. If additional filming is required, the divers are told when they return to the ice hole.

The line tender is the most important individual during the dive. The line tender is the only link the divers have with the ice hole. Due to the varying ice thickness, air bubbles and snow cover on the ice, the divers generally cannot see the hole. Support personnel may shovel paths through any surface snow cover to aid the diver's visibility or to delineate a route or path the divers are to follow.

The divers must rely on the lifeline to return safely. The line must be taut at all times. The line tender must pay out the line if the divers are swimming away from the hole and pull up the slack if the divers are returning to the hole. While the dive is in progress, the tender must give undivided attention to the line.

The third person can run errands and/or help the divers with their equipment, which may include deicing the regulators on the air tanks. This person can also remove new forming ice cover and ice slush in the hole. This person must also keep all onlookers away from the hole and the line tender.

In addition to the equipment necessary for the dives, large quantities of hot water should be at the site. The hot water is used for deicing regulators and other equipment as well as pouring in the divers gloves, boots and wet suits to help them stay warm.
2.4 Operations and safety procedures for under ice diving

The divers and above-ice personnel must follow all standard safety precautions taught in advanced ice diving classes. It is recommended that the divers be Master Divers and hold Ice Diving Certificates. The divers should have a minimum of 15 previous ice dives of at least 20 minutes in duration. They must also be knowledgeable in underwater work capabilities and the signs of and treatment for cold water disorders and ailments.

Exhaustion, brought on by a decrease in body temperature, is the main limiting factor in ice diving. After one hour in the water, the divers exhibit signs of approaching exhaustion. All ice dives should be limited to less than one hour.

As mentioned above, the divers must be securely tied to a lifeline, since this is their only link to the hole. If the divers use the camera cable they are connected to it with short tether lines. This allows them the mobility needed to operate the camera. The lifeline must be kept taut for signaling purposes. Universal signaling should be used. This signaling is a series of groups of pulls on the cable. All personnel connected with the dives must know the signaling system.

The dives are planned to last about 45 minutes, and if possible all filming should be completed from one hole. If the divers must change holes, warm transportation must be supplied to keep the equipment from freezing. The divers should return to the ice hole at least once during the dive to communicate with the dive leader. They and the dive leader can discuss the first portion of the dive and develop a plan for the remainder of the dive. It may be necessary to refilm certain structures and conditions, or the dive can continue as originally planned.

3. UNDER ICE OBSERVATIONS OF ICE/STRUCTURE INTERACTIONS

The measurements and observations of the divers and the analysis of the videotapes and films are reported in this section. The harbors in western Lake Superior, as was mentioned earlier, have significant seiche action. The water is also very cold, but not as cold as the divers once reported, namely \(-2^\circ C (29^\circ F)\) based on their wrist thermometers! It is however within a tenth of a degree of the freezing point at most times when an ice cover is present. This cold water occurrence, which has been precisely measured many times, may explain some of the unusual ice formations observed.
The divers have been under ice ranging in thicknesses from as little as 200 mm (8 inches) to nearly 750 mm (30 inches). Holes in the ice, or sometimes very thin ice, have been observed due to dark objects resting on or in the ice, such as pieces of weedy vegetation.

The harbor water depths are variable and in the range of 1.5 to 3 meters (5 to 10 feet). Bottom conditions are loose silty sediments, which are easily disturbed by the divers presence. Visibility in some harbors has been excellent, up to 30 meters (100 feet); in others, as little as 1 meter (3 feet). The latter type of harbors have noticeable currents, such as from an entering stream or creek.

3.1 Floating pontoon docks in ice

Dark colored, high density polyethylene, foam-filled pontoon tubs have been observed in a number of harbors. The bottoms of the pontoons are not ice-covered due to the insulating effect of the foam in the tub. The ice in the aisles and between the docks is thicker than that attached to the sides of the pontoons. When viewed from the bottom, looking up, the ice is concave and becomes thinner starting about 0.3 meters (one foot) from the side of the pontoon. The ice sheet itself appears honeycombed. Figures 7 and 8 show pontoon docks in the ice. In Figure 8, the dark colored objects are pontoons protruding through the ice sheet (shaded) and surrounded by thinner ice (halo effect). However in a flooded near-shore, cracked-ice area (like shown in Figure 4), the ice completely surrounds the pontoon tubs.

Figure 7. Floating pontoon dock in ice.

Figure 8. Dock pontoons viewed from under the ice. (See text.)
The metal spuds (pipes or rods dropped to, or tapped into, harbor bottom sediments) frequently have small encircling ice collars (due to the metal's thermal conductivity). Although these collars can cause wedging of the spuds in the retainers attached to the sides of the dock members, the docks and spuds are usually moving together in the fluctuating ice. Under these conditions no rubble is formed on top of, or beneath, the ice sheet. (The subsequent description, a laterally restrained floating fuel pier with driven piles, presents a significantly different ice/structure interaction condition.)

3.2 Pile-restrained floating fuel dock

The fuel dock being observed was damaged during its first winter in the ice. The ice reached a thickness of about 750 mm (30 inches). The construction of the floats are the same as described above; however, instead of metal spuds dropped to the bottom, the dock is held in place by four 254-mm (10-inch) pipe piles driven into the bottom. Each pile is connected to the dock with two encircling metal straps or collars, one about 0.3 meters (one foot) above the water line and the second about 0.3 meters (one foot) below the water line.

The piles generated large quantities of ice rubble pieces (similar to those shown in Figure 2). The piles were finally uplifted. Underneath the ice sheet the divers observed 1.2-meter (4-foot) high accumulations of ice rubble pieces. These pieces were found to be gone during a subsequent dive later in the winter. They probably melted when the dock manufacturer installed deicing equipment to limit the amount of damages; or perhaps became displaced under action of currents.

Differential movement between the floating dock in the ice and the unyielding steel pipe piles resulted in the lower set of metal collars being broken from the docks by failures of the welds and metal connections. They now rest on the bottom. In the spring, the fuel pier had to be removed and repaired.

3.3 Harbor entrance pressure ridge

A pressure ridge usually forms near the entrance to one of the small-craft harbors. This harbor is protected by a breakwater. The breakwater is a wall that is formed by a metal bin, filled with sand and capped with concrete, and rests on the harbor bottom. The pressure ridge stands about 1.5 meters (5 feet) high. One would normally expect some ice rubble pieces
under the ice sheet. The divers found none. The ice sheet was about 600 mm (24 inches) thick. Currents in this entrance area were observed, and it is presumed that these currents may have melted or displaced the ice rubble under the pressure ridge.

3.4 Ice attachments to timber cribs and metal bins

Some of the harbors inspected are protected by breakwaters constructed from rock-filled timber cribs or sand-filled metal bins. These breakwaters rest on the bottom and are not damaged by the ice uplift or ice shove actions, although occasionally there is some damage to the tops of the timber cribs, which may be pulled up or displaced by the ice.

The ice frozen to, or next to, these breakwaters is very irregular and unsafe. There may be attachments that are 1.2 meters (4 feet) thick, open water, rubble pieces, or layered ice formations. The layered formations consist of thin, smooth ice lenses or shelves separated by water. The shelves vary from 50 to 300 mm (a few inches to one foot) thick. Meshed in between them are rather cavernous areas or cavities of water and ice crystals, but no firm ice. The entire underwater ice formation is very non-uniform. It is believed that current, seiche action, thermal melting, and other factors cause these formations.

The harbor bottoms next to the metal bins are covered with pea-sized gravel mats. Where needed for toe-protection, rock boulders that measure 0.3 to 0.6 meters (1 to 2 feet) are placed. The ice is thin and scalloped above the boulder-covered areas. It is thicker and rather smooth and uniform above the gravel areas. Next to the bins the water is about 1.5 meters (5 feet) deep. Thermal currents may be generated from the rocks and cause the scalloped effects.

3.5 Piles deiced with compressed air

Bottom-resting compressed air tubes with slits are used to "bubble" next to marina piles and prevent ice uplift. The emitted air is entrained in the water and causes an upward circulation. This water rubs the ice sheet and melts it. With sufficient air, the ice will melt through entirely, and the marina pile will be cleared of ice.

Ice collars form on piles and more so on metal piles than on timber piles. The divers describe them as "crystal clear ice collars, halos of brightness extending down about 100 mm (4 inches) from the surface and 25 mm (1 inch) thick."

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A concave circular area, when viewed from under the ice looking up, forms around the melted-free marina pile. (Figure 9.) The diameter is variable but ranges from 1.2 to 1.8 meters (4 to 6 feet) when thicker ice is present. Similar patterns are sometimes observed on pilings that are not being bubble deiced, but are nevertheless relatively free of attached ice. This results from the seiching pumping action of harbor water, up and down. Full sections of ice, sawed from ice sheets around piles, also frequently show this concave encircling cavity, even when the piles are not being deiced.

Where bubbles are moving water, or where seiches are causing circulations, the ice is very smooth and polished. Irregular formations also develop, such as ice stalactites 0.3 meters (one foot) or more in length, which grow down from the underside of the ice and into the water, and ice rubble pieces (Figure 10). Bubbles follow cracks in the ice, accentuate them, and make them smooth.

4. SUMMARY AND CONCLUSIONS

Ice conditions in small-craft harbors have been observed for many years. For the past four years, observations have been made from beneath the ice sheet as well as from the surface above, to learn how ice attaches to fixed and floating structures, how ice melts, and how ice conditions change with time.
Ice characteristically is non-uniform and is irregular in the vicinity of structures. It may be thicker or thinner, smoother or rougher, or broken or intact, when compared with the central areas of the sheet. Natural phenomena, such as pressure ridges, may be affected by currents and water actions beneath them.

Continued winter observations beneath ice sheets are planned to gain fuller understandings of the ice/structure interactions in small-craft harbors.

5. ACKNOWLEDGMENTS

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The authors also wish to acknowledge and thank the scuba divers, Messrs. John Felix and Harlan Miller, for their diving services and videotaping work.

6. REFERENCES


In order to measure pore pressures in freezing and thawing fine-grained soils in the field, a standard electrical piezometer was modified. With this device, pore pressures and ground temperatures were recorded in freezing and thawing soils in the laboratory as well as in the field. Typically, it was found that pore pressure may increase and decrease in fine-grained soils as ice lenses develop. During thawing, pore pressures decrease as long as downward drainage is not restricted.

1. INTRODUCTION

It is well known that in clay soils an unfrozen water phase exists that separates ice from the mineral and organic soil matrix even at temperatures as low as minus ten degrees Celsius (Roggensack 1978, Phukan 1985). The presence of unfrozen water in fine-grained frozen soils will influence the effective stress conditions in the soil, e.g. during ice lens formation, which is caused by the upward flow of water due to capillary action from the unfrozen portion of the soil mass. Ice lens formation explains the large volume increases which are typical for freezing fine-grained soils. When such ice-rich soils thaw under undrained conditions high pore pressures may develop, which in slopes or below foundations, may lead to total failure (McRoberts et al., 1974) or may result in large settlements under the weight of the soil as the excess pore pressures dissipate (Nixon et al. 1978).

Field measurements of pore pressure changes have been reported for thaw of active zones in permafrost areas (e.g. Chandler 1972, McRoberts et al.)
1974), however no field records exist on pore pressures developing in fine-grained soils prior to, and during freezing. The main reason for this lack of information appears to be that piezometers generally stop working at freezing conditions, or in the case of electrical piezometers, often will be destroyed during freezing. Thus, in order to record seasonal pore pressure fluctuations related to freezing and thawing of fine grained soils, a standard electrical piezometer (in this case, type Geokon 4500-SC) was modified such that it could withstand freezing conditions.

2. PIEZOMETER FOR MEASUREMENT OF PORE WATER PRESSURES IN FREEZING SOILS

The Geokon type piezometers are semiconductor type strain gages which measure the deflection of a diaphragm at its centre (See Fig. 1 (a)). Pressure on the diaphragm causes it to deflect, straining the gages and changing the electrical resistance. The change in electrical resistance is recorded and used as an indication of the pressure applied. The diaphragm is separated from the soil by a porous stone. At below zero degree temperatures, the water in the rigid cavity between the filter stone and the diaphragm freezes, resulting in freezing pressures which may burst the diaphragm. In order to prevent this from happening, the liquid in the cavity adjacent to the diaphragm should not be allowed to freeze. This can be achieved, e.g. by using other fluids such as ethylene glycol or silicon oil instead of water which do not freeze at the temperatures normally encountered. The simplest method of containing the anti-freeze around the piezometer tip is by means of a rubber membrane held around the filter tip, by O-rings and clamps (See Fig. 1(b)). This simple arrangement was initially used (Warren et al. 1987), even though it was found that pore pressures were measured only if the soil was saturated, whereas for non-saturated soils total pressures were recorded. In order to overcome this problem, the piezometer was modified as shown in Fig. 1 (c). The rubber membrane containing the anti-freeze is kept inside the instrument and not in contact with the soil. The entrance to the instrument is covered by a layer of non-woven geotextile rather than by a rigid porous stone to separate the soil from the rubber membrane. Because of the lower heat conductivity of the geotextile, the water will not freeze as readily as when it is in contact with the metal porous stone. Further, due to the flexibility of the geotextile, the build-up of freezing pressures against the membrane, and thus against the diaphragm of the sensor, can be prevented.
3. LABORATORY MEASUREMENTS

A series of pore pressure measurements for freezing and thawing soil were obtained in the laboratory. A column of soil 210 mm in diameter and approximately 400 mm high was contained in an insulated cylinder and frozen from the surface downwards with liquid nitrogen (See Fig. 2). Two, or in some cases three thermistors and one piezometer were installed in the soil to measure ground temperatures and pore pressure changes during freezing and subsequent thawing. At the base of the soil a 30 mm deep layer of clean concrete sand was placed, which was connected to a standpipe filled with water to the level of the ground surface. This standpipe served to provide a continuous supply of water to the bottom of the soil layer, and also to record the volume changes of water during freezing and thawing of the soil. The concrete sand was in most cases separated by a layer of non-woven geotextile from the soil to prevent movement of fines from the soil into the sand layer. The soil, a clayey, sandy silt of very low plasticity, was placed at a water content slightly higher than the liquid limit, in the cylinder and was allowed to consolidate under its own weight for several days, before freezing was started. The location of the piezometer was varied from test to test, to measure pore pressure responses at different depths of the soil column. Typical test results for a piezometer in the centre of the specimen are shown in Fig. 3. The pore pressure increased initially, as the ground froze, but decreased shortly after, reaching the initial minimum value approximately at a temperature of 4°C near the piezometer tip. Subsequently the pore pressure increased to a maximum value of 12 kPa when the temperatures near the surface reached a minimum and the soil near the piezometer tip started to freeze. After this point the pore pressures dropped again reaching a minimum value of -1.6 kPa when the temperature at the piezometer tip was at its minimum value which was slightly below 0°C. Subsequently, during initial thaw the pore pressures rose again, reaching a maximum just before the entire soil was in a thawed state. At this point the pore pressure dropped again reaching a minimum at a temperature of approximately +2°C throughout the sample. After that the pore pressures increased steadily approaching the values measured at the beginning of the test. The burette readings peaked when the minimum ground temperatures were recorded and declined subsequently, slowly approaching the initial water level.

Water contents in the soil were recorded at the beginning and the end of the test and were plotted versus the height of the specimen as shown on Fig. 2. The water content at the start of the test was 24.5%. At the end
of the test the same water content of 24.5% was found at the top of the sample, 21.3% at the centre portion, and 18.3% at the base. In one case a sequence of six freeze-thaw cycles was carried out on the same specimen and the results indicated that the maximum positive pore pressures recorded during soil freezing, increased with increasing number of freeze-thaw cycles. It was further observed that after each thawing cycle the surface of the soil column had settled by about 20 mm, which is equivalent to a strain of 6%. At the end of the six freeze-thaw tests the thawed soil specimen showed a layered structure: a sequence of stiff soil layers about 10 mm in thickness, separated by thin wet zones. This suggest that ice-segregation occurred during the freeze-thaw cycles.

4. FIELD MEASUREMENTS

Modified piezometers were installed in the field at two locations in Northern Canada. However, data were available from only one site at the time of writing this paper. This location is adjacent to an anchored sheet-pile wing-wall of a weir-structure on the campus of Lakehead University in Thunder Bay, Northwestern Ontario, which was built in the fall of 1987 in connection with the reconstruction of a fish ladder. A site plan and a cross section through the instrumented area are shown on Fig. 4. The Sheet piles were driven through a stiff layered silt deposit to a dense glacial till and were tied back by steel anchors to a deadman system of prefabricated concrete anchor plates. The sheet-pile wall was backfilled with a silty-clayey sand. Weep holes were located in the sheet-pile walls near the backfill surface. The difference in head between the upstream and downstream side of the weir ranges between two and three metres, depending on the flow quantities of the river.

Pairs of strain-gauges were mounted on four anchors in the laboratory prior to their installations. A 200 mm long piece of anchor steel was also instrumented with strain gauges and buried adjacent to the real anchors for control of the actual anchor readings and evaluation of possible temperature effects. After completion of the structure in November 1987 the modified piezometer and two thermistors were installed about 2 metres behind the wall adjacent to anchor No. 3 at a depth of 1.0 m below ground surface. The measured values for anchor forces, pore pressures, and ground temperatures are plotted for the time period between November 1987 and December 1988 on Fig. 5. The monthly air temperatures and precipitation data at the Thunder Bay airport reported for this time period are also included in the graph.

The pore pressures decreased with decreasing ground temperatures,
increased for a short period prior to freezing of the soil near the piezometer tip, and then continued to drop interrupted by a short second peak during the time period at which the ground temperature near the piezometer was at its lowest value. The pore pressures reached a minimum of 12 kPa, when the ground near the piezometer started to thaw. During initial thaw the pore pressures rose to a value of zero kPa, but dropped again at the end of April as the ground continued to warm up. After some precipitation in May the pore pressures started to rise, increasing steadily since then, reaching a value of 20 kPa in November 1988. The forces in all 4 anchors reached maximum values during February 1988 when the lowest ground temperatures were recorded. The anchor forces reached minimum values in April after the ground was thawed out and stayed relatively level until fall, with increases in November, when the pore pressures, behind the wall rose at an increased rate.

5. DISCUSSION OF RESULTS

In the laboratory and in the field, alternating pore pressure decreases and increases at the beginning of the freezing period were observed, reflecting the interaction between suction towards the growing ice lenses and pore pressure increases within volume-restrained freezing soil portions. The general decrease in pore pressure which was commonly noticed with decreasing ground temperature adjacent to the piezometer appears to be a result of the accelerated rate of ice lens formation in the ground. The large volume increases which can be expected to occur during ice lens formation are reflected in the laboratory setting by the volume of water flowing into the standpipe as the ground temperature near the piezometer decreased. In the field, volume changes during ice lens formation appeared to be restricted by the anchored-wall systems. Accordingly, increasing anchor forces reflected the increasing freezing pressures during the formation of ice lenses at this stage.

Negative pore pressures recorded for thawing soil in the laboratory and in the field may be explained by the swelling of the overconsolidated soil clusters between the ice lenses during the decrease in freezing pressure as the ice lenses thaw (e.g. Morgenstern et al. 1971; Nixon et al. 1978; Chamberlain 1973). Overconsolidated clay layers between wet joint surfaces were observed in this study at the end of the freeze-thaw cycles.

Once the soil clusters ceased swelling, the pore pressures started to increase again, approaching the stable porewater conditions for the thawed soil. In the field this meant adjustment to the steady seepage conditions as defined by the differences in heads between upstream and downstream
conditions of the weir.

6. SUMMARY AND CONCLUSIONS

The most important findings of this study can be summarized as follows:

1. Relative simple modifications of electrical piezometers allow the measurement of pore pressures in freezing and thawing fine-grained soils in the field.

2. Pore pressure increases may occur temporarily in freezing soils within a restrained mass of freezing fine-grained soil, alternating with pore pressure decreases which develop as water is drawn to ice lenses which form in freezing fine-grained soils.

3. The soil clusters between the ice lenses become overconsolidated due to the effect of the above described negative pore pressures.

4. The degree of overconsolidation appears to increase with increasing number of freeze-thaw cycles in fine-grained soils.

5. During thaw the overconsolidated soil clusters expand as the freezing pressure decreases. The expansion of the clay clusters during thaw is reflected by negative pore pressures, if the thawed water can dissipate readily. Large pore pressure increases in thawing soil as described by McRoberts and Morgenstern, 1974 and Chandler, 1972, appear to develop only if the dissipation of the thawed water is restricted, as e.g. in the case of permafrost, or highly impervious soil at the base of the thawing soil layer.

6. Negative pore pressures in freezing soils and in thawing soils indicate the existence of freezing pressure.

7. The magnitude of the negative pore pressure changes does not necessarily indicate the magnitude of the freezing pressures. Thus, pore pressure measurements in freezing soil behind retaining structures cannot replace the measurements of anchor forces.

8. Because piezometers are relatively easy to install and generally provide reliable data compared to total-load-cells or strain gages installed in the field on existing structures, pore pressure measurements in freezing soils help to identify the development of potential instability problems.

7. ACKNOWLEDGEMENTS

The study was supported by funds provided by an NSERC Development Grant and a Lakehead University's Senate Research Grant.
8. REFERENCES


9. FIGURES

Figure 1. Electrical Piezometer: a) Original, b) First Modification with Tip Protected with Rubber Membrane Balloon, c) Final Modification.

Figure 2. Set-Up for Laboratory Freeze-Thaw Test with Plot of Typical Moisture Content after Completion of one Freeze-Thaw Cycle.
Figure 3. Typical Results of Laboratory Freeze-Thaw Test

Figure 5. Field Observations of Wing Wall, Thunder Bay, Ontario, Canada
Figure 4. Field Installation, Wing Wall of Lake Tamblyn Weir Structure, Thunder Bay, Ontario, Canada
BEARING CAPACITY OF SEASON-FREEZING AND THAWING SOILS
BY HORIZONTAL STRESS CHANGE

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Abstract

The method of foundation bearing capacity increase of thawing soils due to mining is suggested here. The investigations performed show that the bearing capacity and strain ability depend on soil foundation prestressing.

The bearing capacity increase of season-thawing soils is theoretically founded and graphically illustrated. The comparison of test results indicate that the bearing capacity of prestressed foundation is several times more than that of natural and reinforced foundations. Ground settlement on the reinforced prepressed foundation is 4-6 times less than that on the natural and reinforced foundations.

I. The Adjusting System of Season-Thawing Soil Foundation by Stress-Strain State.

One can observe structural bonding discontinuity texture formation when soil freezes. In the process of thawing, soil structure and texture change, structural bonding strength sharply decreases and excess of moisture content results in soil strength decrease, shear and formation of decreased shear strength planes along separate units surface. Clay and loam strength decreases considerably after the freezing-thawing cycle and depends on soil frost texture. As a result of experimental data a new system of foundation bearing capacity increase was suggested due to stress and strain tensor horizontal component change.
The idea of this system is to adjust bearing capacity and foundation settlement in operation and reconstruction on season-freezing and thawing foundations. This is achieved by foundation bearing capacity increase by prestressing in the expected maximal settlement of some sections of buildings (especially long ones). In the expected minimum settlement (for example along the butts of a long building) there appear soil slots filled with thixotropic suspension which takes away shear stress in soil and promotes butt sections settlement increase. Foundation bearing capacity increase is achieved by prestressing with grooves. The grooves are fixed on both sides near foundation. They are provided with cable-embedded blocks. Slotting soil, cables are moved in the designed state by winches alternative switching on. Winches are fixed on the groove. Cables stretching by jacks, set on the groove instead of winches, causes the foundation prestressing. The soil slot is filled with cement-sand mixture. A long building is graphically presented (Fig. I).

The suggested system is applied in the following way. Groove I is rammed down the soil massif. It is supported by cable 3 bended block 2 near the butt part foundation 4 of the building. Groove with block 2 (bended by cable 3) sited on the horizontal line is set opposite each groove I. The number of blocks 2 in the central part of the building correspond to the designed number of reinforcement on a vertical line. Subload 6 is sited on winch platform 5. Block 2 and groove I are set in the butt part of the building. There cable 3 supports only slot 4. Cable 3 ends are fixed on winch 5. As a result of cable 3 stretching by alternative winches 5 switching on there appears a slot in soil. After dropping cable 3 to the block 2 level, cable 3 is disjoined from winch 5 and is stretched by grooves. The slot in the central part of the building is filled with cement-sand mixture. The slot in the butt part is filled with thixotropic suspension. This system makes it possible to adjust bearing capacity and foundation.
Fig. 1 Scheme of building section with adjusted foundation
settlement both in construction and in operation. Due to this system we may equate uniformity of building separate parts settlement (especially of long ones). This is achieved by foundation bearing capacity increase caused by prestressing in the expected maximal settlement plots. Slots filled with thixotropic suspension appear in soil in the expected minimum settlement plots. This system was tested when adjusting a building settlement on the cyclic freezing and thawing foundation.

2. Model Investigations of Various Soil Foundations

Season-freezing and thawing soil foundation might cause damage of a structure. Large unequal foundation settings create special danger as a result of thawing, which in its turn causes decrease of soil mechanical characteristics. Thus, three series of experimental tests were carried out. The aim of these tests was to compare the bearing capacity of non-reinforced, reinforced and reinforced prestressed foundations. The diagrams are shown in Fig. 2.

Fig. 2 Bearing capacity investigation diagrams.

a) non-reinforced foundation;

b) reinforced foundation

c) reinforced prestressed foundation

1-tray; 2-sand; 3-stamp; 4-bonding; 5-plate; 6-frame; 7-pulley; 8-stretcher.
The foundation model material was a mixture consisting of 97% of fine quartz sand and 3% of spindle oil, by weight. Model and natural foundation linear scale was determined by a ratio of strong properties (clutching) of investigated soil types (equivalent material and Karaganda natural loam). The strip foundation model foot is 0.1 m wide. Brass foil strips having section 35.5 x 0.03 mm were used as bondings. Reinforcement was laid in two layers at the depth with a reinforcement step of 30 mm. Three bondings were fixed in each reinforced layer. Foundation earth pressure groove was imitated at one side - a steel plate, at the other side - a steel frame with pulleys (to avoid bonding break in bending flexure) and a stretcher. The load on foundation model was registered by a dynamometer. Load on foundation was applied in steps of 370 N, pressure increase along the foundation foot being 0.016 MPa. The foundation settlement was registered by two flexometers. Nonreinforced foundation bearing capacity tests were carried out up to $S=10$ mm. Reinforced foundation bearing capacity investigations were performed without bonding prestretching but with reinforcement anchorage on the groove. This differs from the experiments, described in 2, when performing similar investigations, bonding setting in soil was used. This series tests were carried out up to $S=10$ mm. While investigating reinforced prestressed foundation bearing capacity, we used bonding prestretching, the value of which was 50 N per each bonding. The groove pressing stress $C_k=0.013$ MPa. Third series experiments were carried out to full bearing capacity lost, caused by bonding abrupt. On the basis of average model tests results, the graphs of foundation settlement dependence on along foot pressure were drawn (Fig. 3)
Fig. 3 Foundation subsidence diagram.

- non-reinforced soil;
- reinforced soil;
- reinforced prestressed soil

Analysis of the test results have shown that reinforced prestressed bearing capacity is 2.3 times more foundation bearing capacity and 1.7 times more foundation bearing capacity (Fig. 3). Foundation settlement on the reinforced prestressed footing is 5-6 times than that on the reinforced foundation; Soil thawing results in foundation setting-in increase due to artificial weather chamber (Fig. 3 It is shown by dotted lines). However, strip foundation doesn't slot during the third series due to soil foundation prestressing.

2.1 Laboratory Tests of Anchor Timbering Models.

Model tests on relative anchor bearing capacity were carried out in the tray measuring 40x20x20 mm on the equivalent soil foundation (with above-mentioned characteristics). Anchor, 1.5 m in diameter, 10 m long, was modeled by a brass pipe, 15 mm in diameter, 100 mm long, assembled at the length of 250 mm from the tray butt by the suggested system of timbering. Drilling cylinder anchor, 1.5 m in diameter and 5 m long, set at the depth of 5 m, was modeled by a brass pipe 3 with shut butts (Fig. 4 b), 15 mm in diameter, 100 mm long, sited at the depth of 50 mm. A steel cable was modeled by a string, fixed in the centre of gravity of anchor models face.
section and stretched through opening 5 in tray butt 1 to flexometer 6 FAO-LICI 6, fixed on stiff corbel 7.

Fig. 4. Experimental installation for anchor models relative bearing capacity tests.

String 4 is bent down from flexometer pulley 6. Plate 8 for load setting 9 is fixed to the string. While investigating load was applied to the string in steps and anchors model displacements were registered (Tables I). Ultimate load on anchor models caused their durability lost and was registered when displacing for 4 mm. Each test was renewed 10 times.

2.1.2 Anchor Models Relative Bearing Capacity Comparison by the Suggested and the Known Systems of Anchor Timbering. Table I analysis shows that anchor model relative bearing capacity of wall assembling by the suggested system is 2 times more than that of the known system. Thus, economic efficiency and expediency of the suggested system is evident: it promotes anchor bearing capacity increase, anchor stretching control and mechanism technology are simplified due to cheap mechanization. Model tests indicate that the quantity of anchors decreases 2 times due to anchor relative bearing
capacity increase by the suggested system of anchor timbering.

Table I

| Num | Anchor models | Applied load | Area of anchor | Anchor ber!! | ! on anchor | model face | ! relative
<table>
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<tr>
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<tr>
<td>N0</td>
<td>! P,N</td>
<td>!surface A, mm²</td>
<td>!bearing</td>
<td>! F,N</td>
<td>!F,N/mm²</td>
<td>!capacity</td>
<td></td>
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<tr>
<td>1.</td>
<td>Anchor model by</td>
<td>the suggested</td>
<td></td>
<td></td>
<td>60.95</td>
<td>1500</td>
<td>0.04</td>
</tr>
<tr>
<td>2.</td>
<td>Anchor model by</td>
<td>the known</td>
<td></td>
<td></td>
<td>4.99</td>
<td>226</td>
<td>0.02</td>
</tr>
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</table>

3. Theoretical Analysis

Bearing capacity of season-freezing and thawing reinforced foundation increases due to two factors:
a) because of vertical reaction at bonding flaxure on settlement and earth shear zones boundary;
b) because of friction resistance along shear surface
So bonding will be stretched when reinforced earth deforms. Each bed redistributed load on a large area by stretching and bending. Friction resistance along shear surface depends on horizontal stresses. Horizontal stresses in reinforced earth plate are higher than in non-reinforced season-freezing and thawing foundation. As for prestressed reinforced earth there is additional prestressing caused by bonding stress transfer on earth shear zone soil or groove. Thus friction along shear surface doesn’t increase prestressed reinforced earth bearing capacity. Horizontal stress promotes prestressed reinforced earth bearing capacity. It may be increased by earth prestressing by sheet pile walls. Investigation results confirm horizontal stress effect. This can be expressed by inequality
\[ \frac{1}{\gamma} P_z \leq P_y \leq \frac{P_z}{\gamma} \]

Inverse inequality is also correct
\[ \frac{1}{\gamma} P_y \leq P \leq \frac{P_y}{\gamma} \]

where \( P_z \) - vertical stress in soil,
\( P_y \) - horizontal stress,
\( \gamma \) - earth pressure ratio

The suggested system is economically advantageous while reconstructing and constructing on season-freezing and thawing soils.

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ESTIMATION OF SHIP AND CONVOY SPEED IN ARCTIC WATERS
IN EVALUATING FLEET DEVELOPMENT EFFECTIVENESS

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ABSTRACT

The substantiation of the construction effectiveness of new ships and icebreakers for the Arctic calls for estimation of their impact on the basic characteristics of the entire transport system. This requires estimation of ship and icebreaker speeds during autonomous motion, as well as for convoys of differing compositions depending on seasonal and multi-year variability of ice and meteorological conditions. Therefore a simulation model was built for the analysis of the arctic marine system. The paper deals with one of the model components associated with selection of ship and icebreaker speeds during autonomous motion, as well as speeds of convoys of various compositions. The selection depends on the technical and operational characteristics of the fleet, as well as on the navigation conditions along the track of the Northern Sea Route (NSR). The use of ice speed information in the economic-mathematical models intended for optimization of the fleet structure and for substantiation of navigation season length, is discussed. The requirements to the collection and study of information on the ice sheet as the shipping environment are formulated.

Increase in freight traffic and extension of the navigation period along the Northern Sea Route leads to a sharp
rise in costs of freight transportation. In this connection higher demands are placed on the reports substantiating the feasibility study, stepwise programmes and general strategy of arctic navigation development (Arikaynen, 1988). In order to help select the optimal periods of navigation on different NSR tracks, an adaptive simulation model that makes it possible to adequately represent the arctic sea operations specifics, was elaborated at the Institute for Systems Studies (ISS), the USSR Academy of Sciences (Arikaynen and Levit, 1988).

It is natural that no model of whatever transport system, nor feasibility study, can do without some assumptions about the motion speeds of the transport means used, because to a largest degree it provides for their productivity. However, motion speeds in arctic waters depend on a far larger number of parameters (and are suffering a stronger influence of chance factors) than in traditional transport systems. Hence, employment of simulation techniques.

One of the possible speed estimation procedures in simulating such systems is the setting of average speeds and their dispersions on the assumption that real speeds change in a random way, according, say, to the normal distribution law. The disadvantage of this approach consists in that the data should be set for all types of ships, tracks, seasons and navigation complexity classes. This substantial volume of information for new makes of ships and different shipping conditions is believed to bear a largely subjective character. Besides, the speeds estimated through random generation, will make the model itself (or the feasibility analysis) totally blind. It will not allow any analysis or identification of reasons for some or other results. In the final count it may lead to random and unprovable speed manipulations and, as a consequence, to lack of confidence in the simulation results.

In view of the above, a different approach was adopted—simulation of specific conditions of navigation on the route correlating with the given navigation complexity class and calculation of specific speeds of specific types of ships in specific conditions. In this case simulation (and estimation of its validity) of navigation conditions are based on multi-year statistical data and the commonly used distinct hypothesis, whereas estimation of speeds at which specific classes of ships
move in these conditions will fully rely on their technical parameters. It will be open to detailed expert discussion and, if necessary, to carefully designed correction.

However, this approach presupposes solution of two interdependent problems:

- formation of a set of parameters that describe the navigation conditions on the route, the parameters exerting the strongest influence on the ship motion speeds;

- identification of the relationship between the speeds of ships and convoys, on the one hand, and their technical characteristics and specific navigation parameters, on the other.

Solution of the former has been treated by us before (Arikaynen and Levit, 1988) Below are given the approaches to solving the latter.

As is known, the influence of the basic parameters of ice on the speed of ships and icebreakers is amply represented in the works of the Arctic and Antarctic Research Institute (AARI), in (Buzuyew A.Va., 1982) and others. However, the available arsenal of statistical relationships of this kind cannot adequately represent practical needs of the problem handled. It is mainly accounted for by its specifics. In this connection it seems reasonable to present a general approach to estimation of icebreaker speed.

Taking into account the fact that the model uses as the basic input information such figures as 0.1-6, 7-8, 9-10, 10 for ice concentration and different figures for ice sheet thickness (Arikaynen and Levit, 1988) the autonomous icebreaker technical speed is used as standard depending on the above characteristics of ice. For icebreakers of the "Moskva", "Yermak", "Arktika" class dependences were based on the actual field experiments carried out by the AARI, whereas for ice sheets exceeding the marginal capability of icebreakers, they were based on the following relationship:

\[ V_{it} = a \left( \frac{h}{h_{mar}} \right)^4 \]  

(1)

Where \( h \) is the marginal ice sheet thickness attacked by the \( h_{mar} \).
icebreaker's continuous motion at a speed of 1.5 knots. 

\[ h > h_{\text{mar}} \] is the ice thickness attacked by blows, 

\( \alpha \) is the ice thickness attacked by blows, 

\( \alpha = \frac{h}{h_{\text{mar}}} \) is an empirical coefficient.

For prospective classes of icebreakers (i.e. "Taimyr" and "LK-150") speed estimation was based on the available data on the existing classes of icebreakers. Both interpolation and extrapolation taking due account of the icebreakers' power capacity, as well as their width, were employed.

It should be pointed out that the model treats as initial the speed of icebreakers in winter ice, i.e. in the ice that is not yet eroded by the melting processes. The seasonal differences in icebreaker speeds accounted for by the snow-covered ice in winter and the partly melted ice in summer, are determined with the help of the corresponding coefficients. This approach to speed estimation differs from that employed by the AARI where the dependence of icebreaker speed on ice concentration and thickness is estimated for winter and summer periods separately. In our opinion, their approach is historically established and does not represent the icebreaker/ice interaction.

The fact is that in the 1960s when arctic navigation proceeded only in summer, the AARI accumulated initial real-life statistical data on icebreaker motion in summer ice. When they were generalized, the corresponding dependence of speed/ice concentration & thickness was obtained. In the 1970s and 1980s, with the advent of winter navigation in the Arctic, similar data on icebreaker motion in winter ice made it possible to derive averaged dependences differing from those of the summer period. To our mind, the above-said differences can be explained by the following: earlier one could not single out a clear-cut contribution of such a parameter as the degree of ice melting. Therefore, we believe, if one uses the "summer" dependences and then introduces the ice melting coefficient, he thereby will, in fact, consider twice the contribution of this parameter. No less important is the fact that, if the model operates all year round, wherefrom one should switch to "summer" or "winter" dependences.

In view of the above, the model operated with "winter"

*) Design of icebreaker of 150 000 h.p. capacity
dependences only. Besides, it was assumed that the ice concentration means visual assessment of the strength of ice. Estimation of icebreaker speed in the summer ice eroded by melting was determined on the following assumptions:
- according to the AARI field observations, 1-point growth of the melting coefficient in the initial melting period contributes to icebreaker speed growth by 15 to 20 per cent on the average;
- with the ice melting coefficient amounting to 5 points (the so called "rotten ice"), icebreaker of comparatively low capacity moves almost as in ice free water.

Taking into account these two statements, it is assumed that with the growth of the melting coefficient from 0 to 5 points, the icebreaker speed changes in a non-linear way according to the following law:

$$K_c = 0.07 b c (K_0 + K_5) + K_5$$  \hspace{1cm} (2)

where $K_0, K_1, K_2, K_3, K_4, K_5$ - are correction factors for icebreaker speed that considers the ice melting coefficient.
$c$ - is the ice melting coefficient expressed in points;
$b$ takes the values of 1, 3, 6, 10, 15 with the melting coefficient of 1, 2, 3, 4 and 5 points respectively.

If the icebreaker autonomous speeds in the melting ice (estimated with the help of these correction factors) are compared with the factual data on icebreakers' motion in concentrated ice with the melting coefficient of 1 to 3 points, one will see their quite satisfactory proximity.

The icebreaker speed correction factors, considering the influence of the prevalent size of ice floes were calculated with due account of the real estimation of seasonal changes of this parameter by the above five categories. With icebreaker motion in fast ice, the speed correction factor (1-point size of floes) was introduced on the basis of the AARI factual data. It is assumed that icebreaker speed in ice cakes and small ice cakes (5-point size of floes) corresponds with its speed in a lead, and speed growth from 2 to 5 points occurs in a non-linear way according to the following law:
where $K_2, K_3, K_4, K_5$ are correction factors for icebreaker speed with 2, 3, 4 and 5 point size of floes. Thus, for 1-2-and 5-point size of floes, and for 3-and 4-point size of floes the AARI factual data and the interpolation data based on the abovesaid assumption were used respectively.

The icebreaker speed correction factors taking into account ice hummocking were calculated on the basis of the Serghyev nomogram (Sergeev, 1978). Initially the reference ice thickness was determined - it depended on the thickness of level ice and its hummocking coefficient in points. Then the icebreaker speed in the reference ice thickness was estimated. Given the speed in level ice, the correction factor for hummocking was derived from the following equation:

$$K_{hum} = \frac{V_{ref}}{V_{lev}}$$

Estimation of the influence of snow on ship motion speeds was based on the AARI research conclusions. It was assumed that:

- the snow less than 10 cm thick does not influence the icebreaker speed;
- the snow 20 plus cm thick has a similar influence on the icebreaker speed as level ice of the same thickness;
- young and first-year ice has snow-cap not more than 10
These three statements are considered when correction factors for snow thickness are calculated according to the following formula:

\[ K_{sn} = \frac{V_{sn}}{V_{lev}} \]  

where \( V_{sn} \) is the icebreaker speed in snow-ice sheet; \( V_{lev} \) is the icebreaker speed in level ice.

The AARI data on the ice pressure coefficient (Buzuyev, 1982) were assumed as a basis for estimation of the ice pressure influence on the icebreaker autonomous motion speed. These data represent the icebreaker speed response to motion in concentrated ice of the same thickness under ice pressure and without it. As the real-life information on the ice pressure coefficient is generalized only for ice pressure of 1 or 2 points, the adopted assumption that the coefficient of 3-point ice pressure is equivalent to that of 2-point ice pressure with the next grade ice thickness. Thus, the 3-point ice pressure coefficient for ice 20 cm thick is equal to that of 2-point ice pressure and ice 50 cm thick. Unlike all other hypotheses suggested by us, this one cannot be checked up on the entire range of thicknesses and icebreaker motion speeds in concentrated ice under 3-point ice pressure. However, certain observations (May, June 1971, June, July 1975) give grounds to believe it is quite acceptable.

There were certain difficulties in estimating the influence of limited visibility on the icebreaker speed, as various authors employ different approaches to estimating it. According to A.Ya. Buzuyev, in limited visibility the speed of the icebreaker decreases, if it

- moves autonomously, by 10 % on the average;
- convoys one ship, by 15 %;
- convoys several ships, by 25 %.

We assumed these data as a basis because they provide for differentiation of three different kinds of navigation. However, such estimates do not consider the specifics of icebreaker motion in ice of different thicknesses. It is
obvious that if the icebreaker operates in young ice, limited visibility does not influence its speed, as in this case it moves straight ahead. In ice thicknesses approximating the icebreaker's capability, the influence of limited visibility will be maximum.

Proceeding from these two statements, as well as from the above-said AARI's estimates, the correction factors for limited visibility were determined:

- in young ice they are 1.0;
- in ice thicknesses amounting to and exceeding the icebreaker's capability, they are: in autonomous motion - 0.90; in convoy of one ship - 0.85; in convoy of 5 ships - 0.75;
- the coefficients within the range of young ice - icebreaker capability were derived by linear interpolation.

Autonomous motion speed estimation for transport vehicles of various icebreaking capacities was obtained by a procedure similar to that used for autonomous motion of icebreakers. However, it had some peculiarities connected with the vehicle's specifics.

The calculations were made with respect to ships of five classes: L1, UL, ULA-1, ULA-2, ULA-3, and the ships of ULA-1, ULA-2 and ULA-3 class are supposed to have icebreaking capability of 0.7, 1.0 and 1.3 meters respectively. Potentials of ships of L1 and UL class are treated by the model in conformity with the classification as per Register of the USSR.

The ship speed in ice of different thicknesses and 3-4, 7-8, 9-10 point concentration is given as speed decrease coefficients in ice-free water (rather than in absolute figures). Thereby we facilitate input of information on the motion speed of any ship in ice: it is sufficient to set the speed in ice-free water.

The calculation of correction factors that consider the influence on the ship speeds of different ice parameters is guided by the following:

- for ships of L1, UL and ULA-1 class the AARI factual data on ships of the "Povenets", "Volgoles" and "Amguema" type were used, with due consideration of their icebreaking capability to develop a safe speed in ice of different thicknesses.

- for ships of ULA-3 class the data on icebreakers of the
"Moskva" type were used, though adjusted towards lower figures. The correlation between the ships' and icebreakers' icebreaking capability was also taken into account;

- for ships of ULA-2 class random data on the ships of the "Norilsk" type were used. Besides, linear interpolation between the data on the ships of ULA-1 and ULA-3 class was applied.

The calculation of speed of a specific convoy is based on the following principles:

- the convoy's speed is determined from the correlation of the icebreaker speed and that of the slowest ship in the convoy in ice free water. Therefore the icebreaker's capability to develop the marginal speed, especially in thin ice, is limited by the capability of the ship to follow the icebreaker in the lead;

- according to the AARI recommendations, in the range of speeds of 5 knots and less, the operational speed of autonomous motion is equal to the technical speed. Given that, time charts of motion of different class icebreakers (in convoy) were designed. They served to determine coefficients for transition from icebreakers' autonomous motion speed to their convoying speed. In this case speed decrease, accounted for only by one difference in the icebreaker's and ship's speeds in ice free water, is equal to

\[ V = K_{corr} (V_{ib}^{fw} - V_{fs}^{fw}) \]  \hspace{1cm} (6)

where \( V_{ib}^{fw} \) and \( V_{fs}^{fw} \) are the icebreaker's and ship's speeds in ice free water. Then the highest possible speed for the icebreaker, in joint motion with the ship in ice \( h \) thick is equal to

\[ V_{ib}^{max} = V_{ib}^{aut} - K_{corr} (V_{ib}^{fw} - V_{fs}^{fw}) \]  \hspace{1cm} (7)

where \( V_{ib}^{aut} \) is autonomous icebreaker speed in ice \( h \) cm thick without allowance for ice pressure or visibility. The correlation makes it obvious that the icebreaker speed in ice free water should not exceed that of the transport vessel. The speed \( V_{ib}^{max} \) serves as the basic one in estimating the speed of
"Moskva" type were used, though adjusted towards lower figures. The correlation between the ships' and icebreakers' icebreaking capability was also taken into account;

- for ships of ULA-2 class random data on the ships of the "Norilsk" type were used. Besides, linear interpolation between the data on the ships of ULA-1 and ULA-3 class was applied.

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$$\Delta V = K^{corr} (V_{fw}^{ib} - V_{fw}^{fs})$$

where $V_{fw}^{ib}$ and $V_{fw}^{fs}$ are the icebreaker's and ship's speeds in ice free water. Then the highest possible speed for the icebreaker, in joint motion with the ship in ice $h$ thick is equal to

$$V_{ib}^{max} = V_{ib}^{aut} - K^{corr} (V_{ib}^{fw} - V_{fs}^{fw})$$

where $V_{ib}^{aut}$ is autonomous icebreaker speed in ice $h$ cm thick without allowance for ice pressure or visibility. The correlation makes it obvious that the icebreaker speed in ice free water should not exceed that of the transport vessel. The speed $V_{ib}^{max}$ serves as the basic one in estimating the speed of
a convoy consisting of 1 to 5 vessels.

Besides, in real conditions the vessels' motion in a convoy is determined by the state of the lead behind the icebreaker. The influence of this factor for loaded vessels was determined via the following correlation:

$$\Delta V = 1 - A \frac{n}{h} \left( 0.1 S_i \right)^b$$

(8)

where $\Delta V$ is decrease in the speed of the convoys consisting of $n$ vessels of various icebreaking capabilities; $h$ is ice thickness; $S_i$ is ice concentration, in points; $A, b$ are coefficients obtained for ships of "LI" and "UL" class by processing the real-life data, whereas for ships of "ULA-2" and "ULA-3" class - by extrapolation.

In accordance with (8), correction factors for the speed of a 1- to- 5- ship convoy in 9-10 point ice concentration (without any ice pressure ) are calculated. As the calculations show, in 3-4-point concentrated ice the abovesaid coefficients are practically equal to 1.0 throughout the range of ice thicknesses. For 7-8-point concentrated ice these coefficients are considered in the model by means of linear interpolation of their values for 3-4-point and 9-10-point concentrated ice. There are no data on the motion of loaded and unloaded vessels. It was supposed, therefore, that the speed of a convoy containing at least one unloaded ship of any icebreaking class, is 10 % less than that of a similar convoy of loaded vessels.

There are certain difficulties in estimating the influence of ice pressure on the speed of a 1-5 ship convoy. We have no generalized real data of that sort. In this connection we were obliged to assume that an icebreaker plus one ship (in ice of 1-point pressure) gets the same resistance as in autonomous motion in ice of 2-point pressure, while an icebreaker plus two ships in ice of 1-point pressure is handicapped to the same extent as with one ship in ice of 2-point pressure. The correction factors for ice pressure of 2 or 3 points were determined in a similar way, i.e. the correction factor for ice pressure of 2 points and ice 20 cm thick is assumed to equal
the correction factor for 1-point pressure and ice 50 cm thick, etc. Two aspects are most important in the suggested approach to estimation of ice pressure influence:

- generalized factual information with respect to the influence of ice pressure on icebreaker autonomous motion serves as the input data;

- there must be a single approach to estimating the speed of any convoy irrespective of icebreaker class and number of ships.

If the icebreaker leads only one ship, possibility of towing is provided for. For that, coefficients of increasing the convoy's speed, if the ship is towed by the icebreaker, are determined on the basis of the AARI data.

Thus, existence of certain gaps in the data on icebreakers' and ships' speeds was compensated for by interpolation and extrapolation and by employment of a number of hypotheses. It was dictated by the need to consider the icebreakers' and ships' speeds in ice against the entire range of ice sheet parameters.

Summing up what has been said, one may draw a conclusion that at present, for the feasibility studies of a strategy of arctic fleet development (employing mathematical economic modelling tools), of great importance is identification of reliable dependences between the motion speeds of convoys of various compositions (with due account of icebreaker capacity, transport ship icebreaking capability, their number and amount of load) under some or other ice conditions. The solution of the above problems will contribute to higher reliability of feasibility studies for long-term fleet development. It will have great national economic significance and make it possible to rationally use hundreds of millions of roubles.

REFERENCES:


ANTARCTICA, AS SEEN BY A SHIPBUILDER

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Manager,            Shipbuilding Group
Technical Marketing Research

ABSTRACT

In January - March 1988, a group of representatives from Rauma-Repola Oy, Finland, and the Ship Laboratory of the Technical Research Centre of Finland (VTT), attended a journey onboard the Soviet antarctic research ship "Akademik Fedorov" built by Rauma-Repola Oy Rauma Shipyard - to make ice performance tests, ice load measurements on the ship's hull and propulsion shafting, and observations of the actual antarctic conditions, in connection with the ship's normal station supporting and research operations in the area. This testing project - being initiated by the shipyard - was carried out in cooperation with the Arctic and Antarctic Scientific Research Institute of the USSR, and the Technical Research Centre of Finland.

1. THE SHIP

"Akademik Fedorov" was delivered by Rauma Shipyard September 10th, 1987 to the USSR State Committee of Hydrometeorology. The shipbuilding contract was signed December 20th, 1985, thus the delivery time was less than 21 months. The ship departed Leningrad October 25th, 1987 for her maiden voyage to Antarctica, as scheduled.

The ship is entirely tailored to its specific tasks and requirements, such as transporting personnel of the Soviet Antarctic (yearly) Expeditions, transporting and delivering fuel, provisions, equipment and other materials to the antarctic research stations, serving as
an independent helicopter base, as well as having a hospital, diving centre etc. Also, there are laboratories for hydrology, hydrochemical and ice research, hydrobiology, aerology and meteorology, radiosynoptics, photog­raphy, and computer systems.

The ship is operated by the Arctic and Antarctic Scientific Research Institute ("AANII"). This institute belongs to the organization of the State Committee of Hydrometeorology of the USSR.

The main particulars of the ship are:

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length, Loa</td>
<td>141.2 m</td>
</tr>
<tr>
<td>Length, Lpp</td>
<td>128.6 m</td>
</tr>
<tr>
<td>Breadth, Bmax</td>
<td>23.5 m</td>
</tr>
<tr>
<td>Height, H</td>
<td>13.3 m</td>
</tr>
<tr>
<td>Draft, max T</td>
<td>8.5 m</td>
</tr>
<tr>
<td>Machinery power, total</td>
<td>16500 kW</td>
</tr>
<tr>
<td>Electric propulsion motor</td>
<td>12000 kW</td>
</tr>
<tr>
<td>One Fixed Pitch propeller, dia</td>
<td>5.1 m</td>
</tr>
<tr>
<td>Service speed</td>
<td>15.5 knots</td>
</tr>
</tbody>
</table>

There are accommodations for the ship's crew of 90 persons and for 160 expedition members, totalling 250 persons.

Main cargo spaces (6650 m³) are situated between the deckhouse and forecastle. There are two deck cranes with lifting hooks of both 5 and 50 t, each. Aft of the deckhouse there are research laboratories, special deck machinery for marine research, a helicopter deck with hangar (inside the deckhouse) and flight control tower, and two 10 t deck cranes in the aft corners of the deckhouse. Refrigerated cargo space (1650 m³) is aft of the machinery space. On the top of the forecastle there is a 2 t crane with a folding arm, which when unfolded, can be used as a ladder, to reach for example the high-lying shelf-ice top. See Fig 1, 2 and 3.

The hull form, is a result of careful consideration of many, often opposite factors that affect the performance and characteristics of the ship. A body plan is shown in Fig 4. The stem angle is 26° from horizontal and the side slope angle about 8° from vertical. The propeller operates in a rather large aperture, and the rudder is protected by a strongly built conventional sole piece and an ice knife behind it.
Certain areas of the ship's hull and the propulsion shafting are equipped with instrumentation to measure ice loads and stresses in the structure. This instrumentation is developed and installed by VTT, and it contains an automatic data collecting, processing and recording system for long-term statistical results. When actually testing ice-going and performance, the research team used an extra instrumentation for short-term data recordings. With this equipment it was also possible to register time histories and separate phenomena in selected conditions and situations.

2. THE JOURNEY

In connection with the 33rd Soviet Antarctic Expedition, the ship remained nearly 8 months in the southern hemisphere while on her maiden voyage. The second leg in this program was started in Wellington, New Zealand, on January 30th, and finished in Buenos Aires, Argentina, on March 17th, 1988.

On the abovementioned second leg, a research team from Rauma Shipyards of Rauma-Repola Oy and the Technical Research Centre of Finland, was on board to perform certain tests in addition to the ship's normal operations. Also, a team of top experts from the laboratory of ice-going ships of the Arctic and Antarctic Scientific Research Institute participated in these tests, being on board for the full eight-month journey.

On this leg, the ship called on the following year-round research stations:

<table>
<thead>
<tr>
<th>Station</th>
<th>Lat</th>
<th>Long</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leningradskaya</td>
<td>69°30' S</td>
<td>159°23' E</td>
</tr>
<tr>
<td>Russkaya</td>
<td>74°46' S</td>
<td>136°51' E</td>
</tr>
<tr>
<td>Bellingshausen</td>
<td>62°12' S</td>
<td>58°58' E</td>
</tr>
</tbody>
</table>

Fig 6 shows the ship's route.

As expected, a drifting ice field was met in front of Leningradskaya. About 100 nautical miles of pack ice was crossed at an average speed of 4.2 knots. In front of Leningradskaya there was landfast ice, into which the ship penetrated about 1 mile. This more or less level ice was growing in thickness towards the shoreline. Finally, after some rammings, the ship was moored. The ice thickness was 1.4 m, and the snow cover on it was about 0.7 m.
After leaving Leningradskaya, the same icefield had to be crossed. The way back was easier than the way there. The Ross Sea was crossed in almost open water, and the ship arrived at Russkaya after passing the large outer icefield by navigating along the coastline, without ice but with a relatively great number of icebergs. At Russkaya, the ship was moored in a landfast icefield for the period needed for servicing and supplying the station.

After Russkaya the large outer icefield had to be penetrated. Helicopter reconnaissance located one spot in a rather difficult icefield, where the crossing distance of heaviest ice was shortest. In one phase of the operation, 72 ramminings were counted in 9 hours, and the corresponding proceeded distance was 8 nautical miles.

In addition to the above mentioned events, many different types of ice coverages were encountered. The ship's speed had to be adjusted to each situation. For example, in the dark, searchlights had to be used, since many growlers do not appear on the radar screen. In some cases, the rudder had to be used very often to avoid colliding with bigger iceflees or growlers, in order to maintain higher speed. In an essay like this it is very difficult to give a general description of all the events. The crew is to decide on each case and the decisions have to be made quickly when functioning. The shipbuilder's task is to deliver a ship with enough strength, performance and reliable functions of all equipment and machinery.

3. SUMMARY

The ship's master (having considerable experience in arctic and antarctic ice navigation) characterized the ice conditions encountered during this trip as normal, average ones, without any extremities.

What we could see and experience, was the large number of different forms and degrees of difficulties of ice fields, which could vary very largely and rapidly, from site to site and with time. One must expect and anticipate such events, and possess the necessary tactical and navigational skills for handling the ship, in order to avoid unnecessary risks in performing necessary operations. The strength and performance of the ships in question can be defined quite accurately; however the conditions encountered where the ships have to operate, can be defined only in a probabilistic sense. As already mentioned, the method of handling a ship is very important, with respect to the level of ice loads the ship will experience.
As data is collected from continuous measurements of actual ice loads, it comes easier to determine the conditions encountered with a higher degree of accuracy. This, combined with the knowledge about the functioning of and the way of handling the ship as a whole, will give useful information not only to define the ship’s performance but also to be used for further developments.

Fig 1. General layout plan

Fig 2. Cargo operations in front of the Russkaya station
Fig 4. Body plan

Fig 5. Typical heavy drifting ice field outside Leningradskaya. Height of camera about 7 metres above sea level.
Fig 6. The route of the ship in January - March 1988
BUILDING TECHNOLOGY IN AN ARCTIC CLIMATE
A preliminary report from the building of a Swedish research station on the Antarctic in 1988-89

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ABSTRACT

During 1988-89 Sweden made a scientific expedition to Dronning Maud Land on the Antarctic. One of the reasons for the expedition was to build a research station. In connection with the building of the station the Division of Structural Engineering at Luleå University carried out investigations in the following fields: organization, logistic use of resources, assembly/assembly systems, design solutions and climatic influence on the building.

1. POSITION AND SURROUNDINGS

The research station, which was named Wasa, was built in four weeks in January 1989. It is situated on the nunatak Basen in the mountain chain Vestfjella about 150 km south of the edge of the ice shelf. Its position is S 73 degrees 02' 72" and W 13 degrees 25' 40", see Figure 1. The station is situated 450 m above sea level. Basen consists of vulcanites, mainly basalt. The nunatak, which is about 4 x 1 km in area, is, to a great extent, free from snow during the antarctic summer. The surface is nearly completely covered with disintegrated rock. At the building site this disintegrated rock is mainly of a size from a fist to a football. There is permafrost and between the rocks there is fine material (silt) that makes it extremely difficult to dig in the ground.

Wasa is situated on the westerly part of Basen. Here it has a protected position from the predominantly easterly winds. The station is the first that has been built on a nunatak on the Antarctic inland.
Today we do not know exactly the prevailing climate at the building site. However, we can anticipate that the temperature in winter can go down to \(-50^\circ C\) and wind speeds can be up to 50 m/s or more.

During the building period we found that the climate on Basen was in a middle position between the damper and windier coastal climate and the drier and colder climate in the Heimefrontsfjella a further 200 km to the south.

2. ORGANIZATION AND PLANNING

The researchers and building materials were carried by the ice-strengthened bulk cargo ship Stena Arctica to the edge of the ice shelf in Dronning Mauds land. The researchers and material were then to be transported from the boat to Basen, situated 120 km to the south. This area had previously only been studied on satellite pictures. In the first stage about 30 people, including researchers, were available for the transportation. The total amount to be transported was about 180 tonnes. This was to be carried on sledges pulled by five Hägglund caterpillar tractors. The distance between Stena Arctica and Basen was 160 km, of which 17 km was on sea ice with many cracks and the remainder on sea floating inland ice, so called ice shelf. The transportation should be arranged so that no shift should normally exceed 10-12 hours. The exposed position and the general risk factor means that an accident can have disastrous consequences. Over a distance of in this case 160 km and a marching speed of 10 km per hour it is suitable to set up a depot half way where the team can be changed. Helicopters in this area are very dependent on the weather. It only takes a minor worsening of weather conditions and they cannot take off. For this reason one should be very careful when counting on helicopter assistance in the preliminary planning.

3. LOGISTIC USE OF RESOURCES

The ground surface in the transport area consisted mainly of wind packed snow which the caterpillar tractors had little difficulty in crossing. Two types of sledges were used. The shape of the runners proves to be of great importance for the tractive force.

When optimizing the size of the load for each separate transport occasion a probability calculation was used regarding damage due to high material stresses. There occurred both machine damage and fatigue failure in frame parts.
Figure 1. Plan and view of the main building at Wasa, the Swedish Antarctic Research Station.
Helicopters were used to transport people and to reconnoitre the way for the transport.

Snow scooters were used to transport material and researchers in the surroundings of Basen. Moreover, snow scooters were used by certain groups of researchers on longer trips. Under the prevailing snow conditions scooters with long belts were found to be preferable to those with wide or double belts. This was mainly because of the fact that they were easier to manoeuvre.

4. OVERALL DESCRIPTION OF THE STATION

Station Wasa consists of two buildings, see Figs. 2 and 3. The main building is made of wood and traditional Swedish building technology has been used to solve problems of construction. The building has a floor area of about 120 m² and rests on a steel frame that leaves about 1.5 to 2 m space between the floor and the ground below. The reason for leaving an empty space under the building is to allow the wind access and thereby avoid the build up of snow drifts on the leeward side.

The main purpose of this building is to function as a base where researchers can rest and go through their equipment. For this reason modern conveniences have been given priority; there is a shower with hot and cold water, a sauna, washing machine, dish-washer, fridge, freezer, electric cooker and microwave oven. The building can sleep up to 12 researchers.

The generator house is placed about 20 m from the main building. It has been put together from three steel containers which rest on a framework of steel beams. The generator house contains two diesel generators for producing electricity, ice melting equipment to provide water, a workshop and storage space.

5. ASSEMBLY/ASSEMBLY SYSTEMS

When planning an expedition like this one with so many uncertainty factors it is important to have alternative solutions. There were three alternative assembly systems to choose between for the building project. One alternative was to build with bulk timber. This method would take up far too much time.

Another alternative was to build in prefabricated modules. The advantage of this method is that most of the installation can be done in advance. The assembly work is relatively fast, assuming machine resources are
Figure 2 (top). Construction of main building at Wasa Swedish Antarctic Research Station, January 1989. Figure 3 (bottom). Overview of building site with the main building to the left and the generator house to the right.
available. One of the disadvantages is the great weight of the individual modules. This puts great demands on the machine side.

A third alternative was to prefabricate building blocks of suitable size and weight and to put them together on site. The disadvantage is that it takes somewhat longer than the module alternative. All installations have to be done on site.

The deciding factor for choosing prefabricated building blocks was the uncertainty that is associated with building and transportation on the Antarctic inland. A basic principle was that as far as possible one should try to use components that in the last resort could be moved by hand. The assembly of the main body of the house was done with the help of a helicopter. This was possible because we had fine weather during the whole of that period. The alternative would have been to lift the blocks into place with the help of jacks. This would naturally have taken longer time.

6. CLIMATOLOGICAL INFLUENCE ON THE STATION

In order to get a better understanding of the climatological factors governing the whole building as well as the separate parts, a number of sensors collecting humidity, temperature and deformation of construction elements were installed. The sensors, in all 16 for humidity, 16 for temperature and 4 for deformation, were placed in 5 separate groups, see Figs. 4 and 5.

The aim with the configuration at each spot is to measure the particular gradients through the wall (humidity and temperature) at representative places. The deformation sensors bridge adjacent wall elements. In this way it will be possible to track correlated changes between humidity, temperature and deformations in specific wall elements.

Logging of sensor data is accomplished as a mean value each third hour 24 hours a day. The logging system is primarily designed for collecting open sea weather data. With anticipated temperatures down to -50°C and the need for continuous unattended operation for 10-11 months, a reliable and energy efficient system was essential.

The system is divided into four totally separate loggers, with triple back-up functions, to minimize or hopefully totally eliminate failures in the logger function.

In coming seasons these measurements will be compared with ocular and manual inspections at the measuring spots.
Figure 4 (top). Displacement gauges (LVDT) left mounted on wall and roof section to measure displacements between different elements. Moisture and temperature module (right). Additional gauges are placed inside the wall and the roof to measure gradients through the thickness of the elements. Figure 5 (bottom). Two data acquisition centrals installed in the station pantry.
7. CONCLUDING REMARKS

It was possible to establish the research station as planned. It's function will now be studied over the coming years.

ACKNOWLEDGEMENT

The project is sponsored by the Swedish Council for Building Research; SWEDARP, the Swedish Antarctic Program; COLDTECH, a foundation in Luleå for the promotion of cold region technology; NOC, Nordic Construction Company; and Luleå University of Technology.
MAINTENANCE ASPECTS OF FLOATING MOORINGS IN GREENLAND

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ABSTRACT

The inspection and monitoring system for the maintenance of the 12 floating mooring systems installed along the west coast of Greenland is presented in this paper.

The mooring systems at Paamiut/Frederikshåb and Narsaq have been selected for more detailed description and presentation of findings.

Procedures for the determination of the actual strength of the mooring arrangement at Paamiut are presented together with results concerning the trends in the combined effects of corrosion and wear and tear. Single elements with degradation faster than the general trend are depicted.

For the mooring arrangement at Narsaq, the presentation has been concentrated on the failure of some of the riser chains and the cause hereof. The possibilities of hydrogen induced failure or failure resulting from defects, arising from the manufacturing process, are being discussed.

1. INTRODUCTION

Floating mooring systems for a variety of vessels have been established in Greenlandic waters. In total 12 mooring systems are now in use along the west coast of Greenland. The main features are as follows:

- Total steel chain length: About 11 km
- Total number of links and shackles: 62,000
- Maximum number of berthing vessels: 79
- Total investment (price level 1987): 26 million DKK
- Total insurance sum of vessels served by the installations: 500 million DKK
This paper deals with some essential maintenance aspects of two mooring systems in Greenland.

The overall targets for maintenance works are evidently twofold:

i Assess the actual state of repair of the arrangement inspected and detect weak elements.

ii Estimate the optimum time for the next inspection. This involves estimates of the rate of corrosion or other deterioration factors.

In order to demonstrate the methods developed and the results achieved, the following two mooring systems are described below:

i Single buoy mooring at Paamiut (Frederikshåb)

ii Multiple buoy system at Narsaq.

2. SINGLE BUOY MOORING AT PAAMIUT (FREDERIKSHÅB)

2.1 Description of System

The single buoy mooring at Paamiut is designed for ships up to 2,200 GRT. It is normally used for larger passenger vessels and trawlers and was installed in 1980.

The floating buoy is connected to a vertical mooring chain which at the sea bottom is fixed to three 40-50 mm steel chains, each connected to a bollard ashore.

The total chain length is about 700 m.

The system was made of a variety of elements, chain lengths and shackles of different sizes, age and origin - all components of course fulfilling the specified requirements.

The layout of the mooring system appears from Figure 1.

2.2 Inspection Procedures

The inspection system, presently in use, was introduced in 1984 as an attempt to quantify and improve the knowledge of the actual composition and its state of repair.

During the inspections, which at present are carried out at 2-3 years' intervals, all elements are lifted out of the water for identification, inspection and measurements.

Dimensions essential for the strength of the system are measured. This means that the effective cross sectional area of the bolt and link for all shackles are determined, taking due regard to corrosion, wear and tear.
On a sample of the population of single chain links in each chain section between two shackles, measurements to determine the effective cross sectional area have been carried out. As the length of a chain section is normally 27.5 m (15 fathoms), this length will typically contain some 130 individual links. Of these, a sample of 5-10% is taken out randomly and the effective cross sectional areas are determined, using a sliding gauge and taking pitting and other detrimental effects into account. The dimensions are measured to 1/10 mm.

It is stressed again that the determined effective cross sectional areas represent combined effects of corrosion and wear in unknown and probably varying proportions.

2.3 Results
2.3.2 General

Only results concerning the chain sections are dealt with below, as these may exhibit both general developments and some additional aspects concerning the establishment of a rational exchange criterion.
### 2.3.2 Distribution of Cross Sectional Areas

An example from one of the bottom chains appears from Table 1.

**Table 1. Inspection of Bottom Chain**

Element No. 1011. Southern bottom chain. Inspection 1984

Common chain link, \( d = 44.0 \text{ mm} \). Nominal cross sect. area \( A_o = 1,520.5 \text{ mm}^2 \).

<table>
<thead>
<tr>
<th>Element No.</th>
<th>Southern bottom chain. Inspection 1984</th>
</tr>
</thead>
<tbody>
<tr>
<td>Common chain link</td>
<td>( d = 44.0 \text{ mm} ). Nominal cross sect. area ( A_o = 1,520.5 \text{ mm}^2 ).</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Measurements</th>
<th>Calculations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameters</td>
<td>Pitting</td>
</tr>
<tr>
<td>( d_1 )</td>
<td>( d_2 )</td>
</tr>
<tr>
<td>40</td>
<td>43</td>
</tr>
<tr>
<td>45</td>
<td>41</td>
</tr>
<tr>
<td>45</td>
<td>43</td>
</tr>
<tr>
<td>40</td>
<td>44</td>
</tr>
<tr>
<td>42</td>
<td>44</td>
</tr>
<tr>
<td>41</td>
<td>44</td>
</tr>
<tr>
<td>40</td>
<td>44</td>
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<tr>
<td>45</td>
<td>42</td>
</tr>
<tr>
<td>44</td>
<td>40</td>
</tr>
<tr>
<td>44</td>
<td>43</td>
</tr>
<tr>
<td>44</td>
<td>42</td>
</tr>
<tr>
<td>41</td>
<td>43</td>
</tr>
<tr>
<td>42</td>
<td>43</td>
</tr>
<tr>
<td>41</td>
<td>46</td>
</tr>
</tbody>
</table>

Mean value: \( A_m = 1,420.47 \text{ mm}^2 \)
Standard deviation: \( = 49.18 \text{ mm}^2 \)
Coefficient of variation \( = 0.035 \)

Graphical as well as \( X^2 \)-tests have been carried out on the samples, and the result is that the cross sectional areas may be assumed to follow the normal distribution on a 95% significance level.

Results from measurements of other chain sections (elements) are shown in Table 2.

It is seen that for each of the elements the coefficient of variation is low, meaning that the cross sectional area has a small variation around its mean value.
Table 2. Inspections 1988. NW Bottom Chain

<table>
<thead>
<tr>
<th>Element No.</th>
<th>Original Diameter (mm)</th>
<th>Mean Area $A_m$ (mm$^2$)</th>
<th>Stand. Dev. (mm$^2$)</th>
<th>Sample Content Nos.</th>
<th>Installation Time Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,017</td>
<td>52</td>
<td>2,132.0</td>
<td>27.7</td>
<td>8</td>
<td>1984</td>
</tr>
<tr>
<td>1,038</td>
<td>52</td>
<td>2,237.4</td>
<td>28.4</td>
<td>10</td>
<td>1988</td>
</tr>
<tr>
<td>1,021</td>
<td>52</td>
<td>2,178.9</td>
<td>30.8</td>
<td>8</td>
<td>1984</td>
</tr>
<tr>
<td>1,037</td>
<td>52</td>
<td>2,219.9</td>
<td>57.8</td>
<td>10</td>
<td>1988</td>
</tr>
<tr>
<td>1,036</td>
<td>52</td>
<td>2,235.9</td>
<td>22.1</td>
<td>10</td>
<td>1988</td>
</tr>
<tr>
<td>1,033</td>
<td>52</td>
<td>2,151.6</td>
<td>52.3</td>
<td>10</td>
<td>1986</td>
</tr>
<tr>
<td>1,035</td>
<td>52</td>
<td>2,256.6</td>
<td>32.3</td>
<td>10</td>
<td>1988</td>
</tr>
<tr>
<td>1,026</td>
<td>52</td>
<td>2,111.3</td>
<td>44.1</td>
<td>9</td>
<td>1984</td>
</tr>
<tr>
<td>1,027</td>
<td>52</td>
<td>2,153.1</td>
<td>32.6</td>
<td>10</td>
<td>1984</td>
</tr>
<tr>
<td>1,028</td>
<td>52</td>
<td>2,151.9</td>
<td>40.3</td>
<td>10</td>
<td>1984</td>
</tr>
<tr>
<td>1,029</td>
<td>52</td>
<td>2,068.1</td>
<td>61.8</td>
<td>8</td>
<td>1982</td>
</tr>
</tbody>
</table>

It should be noted that although the cross sectional area $A$ has a good fit to the normal distribution, conclusions on this basis regarding values apart from the mean values must be drawn with great care.

What has been found here is the fit to the normal distribution of 'frequent' values of $A$ and extreme values of $A$ may fit closer to other distributions.

Evidently, this presents a difficult task of determining the cross sectional area which shall be compared with the design value in order to establish the exchange criterion.

The Danish Code of Practice presents a clear procedure in that respect, but, unfortunately, it is based on the assumption that 'some of the weaker elements may help the others', which is not the case here. And the longer the chain, the greater the possibility of finding an element with cross sectional area below the design value.

However, this code in combination with the application of safety factors on loads and materials according to the Danish Code of Practice for security and loads (DS 412) leads to criteria in line with common practice. A comprehensive study of the reliability of the elements is at present in progress and should lead to a more rational determination of the exchange criterion.
2.3 Reduction Rates

Based on inspections and measurements in each of the years 1986 and 1988, reduction rates for the cross sectional areas of the chain sections may be assessed as shown in Table 3. (The results from the inspection in 1984 are disregarded in this context, as they exhibit systematic - but unquantifiable - deductions in order to be on the safe side.)

Table 3. Reduction Rates. NW Bottom Chain

<table>
<thead>
<tr>
<th>Element No.</th>
<th>Original Dia.</th>
<th>1986</th>
<th>1988</th>
<th>Reduction Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>( A_m )</td>
<td>( D_m )</td>
<td>( A_m )</td>
</tr>
<tr>
<td>1,017</td>
<td>52</td>
<td>2,133.0</td>
<td>52.11</td>
<td>2,132.0</td>
</tr>
<tr>
<td>1,021</td>
<td>52</td>
<td>2,182.3</td>
<td>52.71</td>
<td>2,178.9</td>
</tr>
<tr>
<td>1,026</td>
<td>52</td>
<td>2,127.4</td>
<td>52.05</td>
<td>2,111.3</td>
</tr>
<tr>
<td>1,027</td>
<td>52</td>
<td>2,138.6</td>
<td>52.18</td>
<td>2,153.1</td>
</tr>
<tr>
<td>1,028</td>
<td>52</td>
<td>2,185.6</td>
<td>52.75</td>
<td>2,151.9</td>
</tr>
<tr>
<td>1,029</td>
<td>52</td>
<td>2,123.9</td>
<td>52.00</td>
<td>2,068.1</td>
</tr>
</tbody>
</table>

It is seen that the reduction rates vary from practically zero to 0.35 m/year.

It should be noted that element No. 1,017 with the lowest reduction rate, is situated near the mooring buoy at a water depth of about 25 m. One could have expected a reduction rate above average because of possible movements of the chain section over the sea bottom, but apparently this is not the case. The chain section may even be influenced by the cathodic protection of the floating steel buoy.

The rest of the chain sections shown in the table are located closer to the shoreline, with element No. 1,029 being fixed to the bollard ashore.

The determination of the reduction rates should be treated with caution, because of the statistical method used and the relatively short time lapse between the inspections. However, the results are in line with corresponding measurements of elements in other mooring arrangements along the coast.

2.4 Other Features

It is believed that the above described procedures may justify a longer time lapse than two years between these thorough inspections. The inspection procedures, the monitoring and evaluation system seem to constitute a tool by which reliable estimates of reduction rates can be determined.
However, there remain secondary elements, the failure of which could be fatal to the proper functioning and which may not be straightforward predictable. Experienced features in this respect have been:

1. Hinge effects, i.e. for instance for shackles, connected directly to a mooring buoy.

2. Corrosion of forelocks in shackles. Significantly faster corrosion of traditional forelocks may necessitate very costly rehabilitation works.

3. Lack of forelocks in shackles.

4. Failure of elements due to mechanical overload. A broken bottom chain, discovered by the load from the anchor of a drifting trawler 6 months earlier.

5. Failure of elements due to manufacturing defects. An example of this is dealt with in section 3 below.

These and other deficiencies, which may occur randomly, require more frequent, but less profound surveillance. Visual inspections, carried out partly by diver, may reveal lack of coherence of the mooring system in time.

3. MULTIPLE BUOY SYSTEM AT NARSAQ

3.1 Description of System

The mooring system comprises 12 mooring buoys, each connected by 20 mm riser chains to 62-68 mm bottom chains, fixed with anchor blocks of reinforced concrete.

The mooring system has been designed for fishing vessels up to about 20 GRT. It was taken into use in 1982 and has not been subject to profound inspections until 1988. The layout is shown schematically in Figure 2.

![Figure 2. Multiple Buoy System at Narsaq](image-url)
3.2 Failures

During a storm in January 1988, two of the 20 mm riser chains broke. The subsequent inspection and repair revealed one more broken riser chain. All three chains had broken at the lower end 2-4 m from the connection to the bottom chain.

3.3 Investigations

The mechanical and metallurgical tests were carried out by the Danish Welding Institute and the Danish Corrosion Centre. The broken chains have been made of high tensile alloy steel with a rupture strength of about 1,400 N/mm and a chemical composition as follows:

<table>
<thead>
<tr>
<th>Element</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>0.18%</td>
<td>0.23%</td>
</tr>
<tr>
<td>Si</td>
<td>0.10%</td>
<td>0.30%</td>
</tr>
<tr>
<td>Mn</td>
<td>0.75%</td>
<td>1.40%</td>
</tr>
<tr>
<td>Ni</td>
<td>0.40%</td>
<td>0.50%</td>
</tr>
<tr>
<td>Al</td>
<td>0.020%</td>
<td>0.004%</td>
</tr>
<tr>
<td>B</td>
<td>0.002%</td>
<td>0.004%</td>
</tr>
<tr>
<td>C</td>
<td>0.2%</td>
<td></td>
</tr>
<tr>
<td>P</td>
<td>max. 0.030%</td>
<td></td>
</tr>
<tr>
<td>S</td>
<td>max 0.030%</td>
<td></td>
</tr>
</tbody>
</table>

Breaking load: 500 kN. Proof load: 250 kN (certified).

Visual inspections of the broken chain sections revealed no signs of extraordinary wear and tear and local defects. The effective cross sectional area for the chain was determined to 90% of the original area (mean 282.5 mm², = 5.5 mm²). This corresponds to a reduction rate of 0.1 mm/year.

Figure 3. Old crack, comprising 85% of the area. Breaking load 98 kN.
Break load tests carried out on the chain sections showed breaking loads ranging from 96 to 525 kN. The chain exhibited a yielding residual rupture with an old crack in the central part of the bar as shown in Fig. 3 and 4.

Calculations of the chain forces during the storm were carried out and compared with the model tests executed during the design phase. It could be concluded that the maximum chain forces would not exceed about 30% of the certified proof load.

The Danish Welding Institute and the Danish Corrosion Centre concentrated their investigations of the failure cause on the following two possibilities:

i. Quenching cracks developed during manufacture
ii. Hydrogen induced damage.

The conclusion was essentially based on the following findings in combination with the basic information above:

- No new cracks (from the storm) with a different corrosion appearance were found
- Pilot cracks (under 45° with the rupture direction) were very scarce or missing
- Hydrogen induced cracks often exhibit signs of stepwise crack development. No signs hereof were found, but this could be blurred by the corrosion.
- Chemical tests revealed no signs of hydrogen sulphide.

On this basis it was concluded that the failures most likely were due to cracks developed during the manufacturing process, unless it could be clearly evidenced that the chains had been proof loaded in their full extent upon manufacture.

On the other hand it is stated that this type of steel is susceptible to hydrogen absorption even under moderate corrosion conditions. Steel types with rupture strengths above 800 N/mm² should be avoided for mooring purposes in order to eliminate the risk of hydrogen induced cracking.

4. CONCLUSIONS

The described monitoring and assessment procedures seem to represent an effective tool for maintaining the strength and the stability of the floating mooring systems.

However, it should be stressed that there are other deficiencies than those related to corrosion/deterioration due to the environment and normal use.

Therefore it is essential to realize that although the above described monitoring schedules may lead to wider time intervals between necessary overhauls, intermediate inspections may be necessary in order to ensure the systems' overall coherence and to follow the developments of the state of repair of certain elements exposed to extraordinary wear and tear.
SCIENTIFIC OCEAN DRILLING IN THE POLAR REGIONS

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A. Meyer, E. Taylor

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ABSTRACT

The Ocean Drilling Program (ODP), an internationally funded scientific research program recovers core samples and data from boreholes in the deep waters of all the world's oceans. The drillship JOIDES Resolution (registered name SEDCO/BP 471) utilized in ODP, has proven itself a remarkably stable drilling platform for work in high latitudes. Exploration has taken place in previously undrilled high latitude deep water sites. In the northern hemisphere we have cored in Baffin Bay and the Norwegian-Greenland Sea. In the southern hemisphere we have drilled and recovered samples from the Weddell Sea and Prydz Bay, Antarctica; and the Subantarctic South Atlantic and Indian Ocean. In these areas, the successes of the JOIDES Resolution has been enhanced by an accompanying ice support vessel which monitors ice movement. In particular, the use of the state-of-the-art support vessel Maersk Master in our Antarctic studies has enabled drilling operations to continue in ice-laden areas due to Master's capability in towing and moving ice.

1. INTRODUCTION

The Ocean Drilling Program (ODP) is a long term (10-year) program of basic research toward understanding the evolution of the solid earth and its environment through the recovery and analysis of core samples from the floor of the world's oceans (Rabinowitz et al., 1984, 1985). To accomplish this, scientists from around the world participate in a continuous series of expeditions, each about two months in duration (Fig. 1), aboard one of the world's most advanced dynamically positioned
Figure 1. Locations of areas where the Ocean Drilling Program has conducted operations as of February, 1989.

drillships -- the JOIDES Resolution (SEDCO/BP 471). On these cruises, scientists collect core samples from beneath the ocean floor in order to better understand the ages of ocean basins and their processes of development, the re-arrangement of continents with time, the structure of the earth's interior, the evolution of life in the oceans, and the history of worldwide climatic changes. That knowledge, in turn, gives us a more complete understanding of the planet Earth - her past, present, and future. Nowhere is this more critical than the polar regions, where massive ice caps contribute to the latitudinal thermal gradients that produce global circulation, the engines which drive our climate. Yet the Earth's high latitude regions represent a major deficiency in our understanding of key climatic changes which have had a global impact on the biosphere, the atmosphere, the oceans and ultimately the lithosphere. The inhospitable nature of these regions to people and equipment
have posed large but not insurmountable technical challenges to ODP (Larson and Serocki, 1974; Harding, 1987). We have only recently begun to amass the geological data in these regions that will help further our understanding of the oceanic paleoenvironment and our climate.

2. THE DRILLSHIP

Some of the major operational features of 471 ft., 18,636 ton JOIDES Resolution include (Foss, 1985):

i) Large, stable-drilling platform capable of operating effectively in most ocean environments.
   - A station-keeping system that can hold the ship to ± 2% water depth with wind limits of 45 kts., gusts of 60 kts., significant wave height of 15 ft. (5 m), maximum wave height of 27 ft. (9 m), and surface currents of 2.5 kts., provided the prevailing environment is within 30° of bow or stern;
   - High latitude capabilities (ice-strengthened hull);
   - 14,700 kilowatts of available diesel electric power, giving the ship an average cruising speed of 13 knots when underway;
   - Berths for up to 50 scientific and technical personnel and 65 drilling and marine crew;
   - An operational endurance of 120 days, largely due to storage capacity for over one million gallons of fuel.

ii) A long drill string with associated drilling systems:
   - A 30,000 ft. (9150 m) tapered drill string handled by an automatic pipe racking system;
   - A 202-ft. (61.6 m) high derrick incorporating a variable speed electric top drive and 400-ton (400,000 kg) in-line heave compensator capable of a 20-ft. (6.1 m) stroke;
   - Two core-winches with 31,000 ft. (9,450 m) of wireline.

iii) State of the art science equipment and laboratories (Kidd et al., 1985):
   - Includes a seven-story (12,000 square feet) structure, with state of the art laboratories for petrology, sedimentology, paleomagnetics, chemistry and gas, physical properties, paleontology, thin sections, X-ray diffraction and fluorescence, downhole logging, and geophysics as well as modern facilities for photography, electronics and refrigerated core storage. While the ship is approaching or leaving drill sites, digital single-channel seismics are recorded
and processed in the underway geophysics laboratory. The JOIDES Resolution is also equipped with a research-oriented computer system. Two VAX computers serve as a central processor and data library for 50 microcomputers distributed throughout the laboratories.

3. SCIENTIFIC OBJECTIVES

The scientific and technical objectives for the ODP were outlined by the international Conference on Scientific Ocean Drilling (COSOD I, 1981) held in Austin, Texas in 1981. In July 1987, a second international Conference on Scientific Ocean Drilling was held in Strasbourg, France (COSOD II, 1987) to review and redefine the scientific objectives in view of the knowledge gained over the past six years.

To achieve the high latitude objectives, two drilling cruises were carried out in the Arctic regions; Leg 104 in the Norwegian-Greenland Sea (Eldholm, O., Thiede, J., Taylor, E., et al., 1987), and Leg 105 in the Labrador Sea and Baffin Bay (Srivastava, S.P., Arthur, M., Clement, B. et al., 1987). Four Legs have been carried out in the Antarctic and Subantarctic regions; Leg 113 in the Weddell Sea (Barker, Kennett et al., 1988), Leg 114 in the southernmost South Atlantic (Ciesielski, Kristoffersen et al., 1988), and Legs 119 and 120 on the Kerguelen Plateau and in Prydz Bay (Barron, Larsen et al., 1988; Schlich, Wise et al., 1988).

4. DRILLING OPERATIONS

Although similar techniques are used for both scientific and industrial drilling, there are major differences stemming from the different objectives. In scientific drilling, the primary objectives are to understand the composition and properties of the strata in the earth's crust. The objective requires continuous coring of undisturbed material; igneous, metamorphic, and sedimentary. This contrasts with the prime objective in oilfield drilling which is to reach the target depth as efficiently as possible with coring done only as appropriate. As a result, scientific drilling may take considerably longer than commercial drilling to achieve the same penetration depth.

Although our planet is almost five billion years old, the sediments of the deep ocean are geologically young (less than 200 million years old) and vary in thickness from zero to several kilometers (1 km average). The upper sediments are usually
unconsolidated and generally consist of non-fossiliferous clays and/or oozes (calcareous and siliceous). Induration generally increases with depth (shales, chalks, limestones) until volcanic basement is reached. A common exception to this is chert, which forms cm-to meter-thick layers in otherwise soft sediment, posing a serious problem for core recovery.

Thus, specialized coring tools have been developed for scientific ocean drilling. For example new coring tools have been developed for coring the harder formations (wireline coring system), to overcome problems related to core disturbance in soft sediments (Advanced Hydraulic Piston Corer; Huey, 1984; Storms et al., 1983), to core areas where lithologies alternate between hard and soft beds (Extended Core Barrel; Cameron, 1984), and to sample rocks from beneath the sea floor in areas of highly fractured rocks with little or no sediment cover.

In addition there are other differences between the operation of the Ocean Drilling Program and oil/gas operation in that ODP:
- operates, in general, in more remote areas of the world's ocean basins.
- drills in much deeper water depths - normally greater than 6,000 ft. (2,000 m) and up to 27,000 ft. (8,700 m).
- spends considerable amounts of time lowering drill strings into open water.
- does not maintain a shore base of operations in the proximity of the drilling. The cost of relocating shore bases every 60 days would be prohibitive.
- does not normally operate with support or standby vessels. For the high latitude operations, however, if either ice conditions or drillship safety are a factor, then ODP does employ the services of a support ice patrol vessel.
- presently drills without a riser. In event of oncoming icebergs, the drillship can easily shift location after simply pulling the drill pipe clear of the sea floor.

5. SCIENTIFIC DRILLING IN POLAR REGIONS
5.1 Norwegian - Greenland Sea (Leg 104)

Eight holes were drilled at three sites to investigate the paleoceanography of the Norwegian-Greenland Sea and the evolution of a passive continental margin, the Voring Plateau (Eldholm, Thiede, Taylor et al., 1987). The axis of the Norwegian current is nearly centered within the operating area. Although the current never adversely affected drilling operations, its effect on the drill string was evident during reentry operations at Site 642 where drilling to a subbottom depth of 1229 m in 1290 m of water required eleven hole reentries. No icebergs were sighted during
5.2 Baffin Bay/Labrador Sea (Leg 105)

Weather conditions were worse during Leg 105 than 104, as recovered material to study the paleoceanographic evolution and the timing of the opening and the spreading history of this part of the North Atlantic Ocean was recovered (Srivastava, Arthur, Clement et al., 1987). The specific goals of the scientists on this cruise were to understand Arctic and Atlantic surface water circulation between 45 and 65 Ma and to investigate the driving mechanisms behind the glacial-interglacial cycles which have occurred during the last 2 m.y.

The Canadian-registered support vessel M/V Chester was chartered for Baffin Bay. Chester, a 54-m-long, ice-classed vessel rated at 1650 hp was employed for ice picket, standby rescue, and personnel duties. As in all ice infested areas, ice management zones mandated by the SEDCO-FOREX Marine Operations Manual were designated around each site. Zone boundaries were calculated several times a day.

5.3 Weddell Sea (Leg 113)

Leg 113 was designed to address questions about climatic evolution during the last 65 m.y., changes which induce powerful feedback mechanisms such as those related to ice albedo and bottom-water formation (Barker, Kennett et al., 1988). To do this, 22 holes were drilled at 9 sites during 65 days of operation. Results indicate that cooling took place in steps, with initial cooling of East Antarctica (most of the Antarctic continent) beginning by the early Oligocene (~32 Ma). A surprising result is that it appears that the West Antarctic (Antarctic Peninsula) ice sheet has been stable since its formation at about 5 Ma.

The JOIDES Resolution was accompanied by the Maersk Master, an 83 m long, 14,900 BHP, Danish ice support vessel. The vessel carried a 1400 m long, 30.5 cm circumference, floating rope with a breaking strength of 1502 kN for ice towing purposes. Watch officers on both the JOIDES Resolution and the Master plotted iceberg locations, and during operations Master was directed to the ice posing the greatest threat. Officers onboard then determined if weather conditions and the size and stability of the ice body would permit the ice to be moved, and if so, the technique to employ. When ice conditions were favorable, geophysical and
biological studies were conducted from the Master.

5.4 Subantarctic South Atlantic (Leg 114)

Twelve holes were drilled at seven sites during Leg 114. The sites form an east-west transect as well as a depth transect across the subantarctic South Atlantic. Weather conditions were often awful. Wind speeds with gusts up to 54 kt and swells caused the vessel to roll 8°-12°. Despite this, only 1.5 days were lost to bad weather and excellent recovery during this leg provides the most continuous Late Cretaceous-Cenozoic (70 Ma to the present) Southern Ocean stratigraphic representation ever obtained. Contained within the sediments are generally well preserved microfauna assemblages. Together with Leg 113 results, the excellent biostratigraphic control combined with a nearly continuous history of geomagnetic polarity reversals provides the first high resolution geochronologic record for this time period in the Southern Ocean. Highlights of the cruise include:

1) the cooling of the Subantarctic surface waters was progressive and punctuated during the Late Cretaceous to Cenozoic. Major cooling episodes occurred near the middle/late Eocene boundary (40 Ma) and the early/late Oligocene boundary (30 Ma),

2) there was a brief warming event at the Oligocene/Miocene boundary (~24 Ma) followed by an advance of the polar front that appears to be related to the opening of the Drake Passage,

3) a major expansion of Antarctic ice is inferred from the presence of ice-rafted sediments in the late Miocene and Pliocene.

4) within the Pleistocene sediments, striking color variations, decreased carbonate content, and increased silica and organic carbon, suggest migration of the polar front migrated over Site 704 at that time (Ciesielski, Kristoffersen et al., 1988).

5.5 Kerguelen Plateau and Prydz Bay (Leg 119)

During ODP Leg 119 eleven sites were drilled along a north-south transect across the Kerguelen Plateau and Prydz Bay to recover material which will allow us to understand the later Tertiary climatic and oceanographic development of Antarctica (Fig. 2). Scientific highlights of the cruise (Barron, Larsen et al., 1988) include recovery of:
Figure 2. Summary of Antarctic sedimentological and biostratigraphic features with climatic implications.

1) a deep-sea sedimentary record of glacial-interglacial oscillations during the past 10 m.y.,
2) microfossils which will allow scientists to document latitudinal fluctuations in surface water masses as well as the overall oceanographic setting, and
3) a continuous Cretaceous/Tertiary boundary.

As with Leg 113, the JOIDES Resolution was accompanied by the Maersk Master for ice management duties. Despite this, icebergs and pack ice were responsible for 4.4 lost days and the early termination of three holes.

5.6 Central Kerguelen Plateau (Leg 120)

Leg 120 completed the latitudinal transect begun during Leg 119. Twelve holes were drilled at 5 sites. This leg concentrated on learning about the early history of the Kerguelen Plateau. Volcanic basement was penetrated three times, revealing that the plateau has a similar composition to the basalt that forms at mid-ocean ridges. The basalt is overlain by a non-marine sequence of mid-Cretaceous age (over 80 Ma old) consisting of weathered volcanics. Immediately overlying the volcanics are Upper Cretaceous chalks, indicating subsidence of the Plateau which has continued to the present. Sediments recovered from the Plateau record climatic changes from warm Cretaceous seas to the frigid Antarctic waters of today (Schlich, Wise et al., 1988).

Operation conditions were challenging in this high southern latitude location during March and April. High winds and heavy seas were a constant factor and a particular concern at the shallow water (~1000 m) sites where the drill string could be more easily damaged. A total of 1.8 days were lost to weather-related down time.

6. CONCLUSIONS

The information gained from high latitude drilling is vital to our understanding of the Earth's climate and the tectonic development of these remote areas. Results from the six ODP high latitude legs have allowed us to establish a chronology for Earth's gradual cooling over the past 40 m.y (Fig. 2). For example, grounded ice sheets occurred Prydz Bay as early as 35 Ma (Barron, Larsen et al., 1988) and around 5 Ma in the Antarctic Peninsula (Barker, Kennett et al., 1988). In the northern hemisphere, glaciation occurred as early 3.4 Ma in Baffin Bay (Srivastava, Arthur, Clement, et al., 1987), 2.9 Ma in the Norwegian Sea (Eidholm, Thiede, Taylor et al., 1987), and 2.5 Ma in the Labrador Sea (Srivastava, Arthur, Clement, et al., 1987). These and other observations are critical to our understanding of global history.
knowledge which is indispensable if we are to understand the consequences of man's influence on this dynamic system.

7. REFERENCES


OFFSHORE DEVELOPMENT IN COOK INLET, ALASKA

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ABSTRACT

Some twenty years ago, a number of unique offshore platforms were installed in Cook Inlet, Alaska. These structures are, to date, still the only oil and gas production platforms operating in an ice environment. Although originally designed for a field life of twenty years, higher oil prices and also the discovery of field extensions now make it likely that several of these platforms will remain in place for as long as fifty years. The paper provides a retrospective of the design and installation methods that were developed for these unique platforms and describes the inspection procedures and corrosion preventive measures that have been taken to prolong the life of these structures.

1. INTRODUCTION

Four oil fields and one gas field were discovered in Cook Inlet, Alaska, see Figure 1, during the early 1960's prior to the discovery of the Prudhoe Bay field. These fields, which are shown on Figure 2, were placed on production with fourteen self contained drilling and production platforms, see Table 1, which were installed in a four year period from 1964 to 1968. A fifteenth platform was added in 1986. The rapid development of these five fields was remarkable because, at that time, Cook Inlet represented some of the most severe environmental conditions encountered anywhere in the offshore oil industry. The combination of ice, tides, current, bitter cold and earthquakes made the design, fabrication and installation of these platforms a considerable challenge.

The discovery of the immense Prudhoe Bay field on the North Slope of Alaska shortly after the initiation of production from Cook Inlet has tended to overshadow these accomplishments and has made this area, in a remote corner of the world to begin with, a bit of a forgotten offshore area. Yet, even today, some 20 years later, these Cook Inlet platforms are still the only fixed offshore drilling and production platforms anywhere in the world that operate in an ice environment.
The initial development plans for the Cook Inlet fields anticipated an economical field life of about 20 years and the platform designs were based on this assumption. These twenty years, however, have now passed and, because of new field extensions and secondary recovery projects, it now appears that several of the fields have a further remaining economic life of 25 years or more. This implies that the platform structures will also need to remain in place for this period of time because replacement, at least with current oil prices, would not be economical. That this platform life extension is possible is attributable to, amongst others, the conservative design criteria assumptions that were used, and also to an early recognition that special measures were needed to arrest a high rate of corrosion of the underwater portions of the platform structures.

2. ENVIRONMENTAL CONDITIONS

2.1 General

Cook Inlet, in southern Alaska, see Figure 1, penetrates for 170 miles (270 km) inland from the Gulf of Alaska. Although weather conditions are somewhat tempered by the proximity of the ocean, the average annual temperature is only about 35°F (2°C). Minimum ambient winter temperature is minus 40°F (-40°C).

Due to the particular shape of the Inlet and its northern latitude, tides are among the highest in the world and range up to 30 ft (9 m). The resulting high currents, 10 to 12 ft/sec (3 to 3.6 m/s), keep the water turbulent most of the time and so much sand and glacial flour is in suspension that underwater visibility is nil. Water temperatures range from a high of 55°F (13°C) in the summer to a low of 29°F (-2°C) in the winter.

Upper Cook Inlet, the area of the oil activity, is covered with ice during the winter months. Ice can be expected as early as November and as late as May. The Inlet is ice free the remainder of the year. During periods of ice cover, the tides move the ice up and down the Inlet at essentially the same speed as the water current, exerting large crushing forces on all objects in its path.

Alaska lies in the Pacific earthquake belt and, as evidenced by the widespread damage from the 1964 Good Friday earthquake, structures in the Inlet are also subject to potentially large earthquake loadings.

2.2 Environmental Forces

The principal environmental force imposed on the Cook Inlet structures is from sea ice during the winter. In 1963, at the time of the discovery of the first oil field, very little information was available on the characteristics and strength of the sea ice generated during the winter months in Cook Inlet. The oil companies involved initiated several research and measurement projects. Results from this research established the basic design criteria that were used for the design of the Cook Inlet platforms. Although detail design parameters differed significantly from company to
company, the resulting maximum loading conditions were quite similar. The design criteria used by one company\(^3\) is shown in Table 2. This table also shows the recently established ice design criteria for Cook Inlet from the API Recommended Practice 2N.\(^5,6\) It is interesting to note that, although individual design parameters are quite different, the resulting design load is essentially the same whether one uses the original design parameters or when one uses the average, but still considered conservative, design parameters from the new API RP 2N.

2.3 Ice Design Criteria

How were the original design criteria established?

The design ice thickness was based on the maximum thickness that could be expected during a 100-year period. This thickness, in turn, is a function of the cumulative degree days below the so-called ice formation temperature. This is the temperature at which new ice will not form, nor will old ice melt. For Cook Inlet water this ice formation temperature is 20°F (-7°C). By extrapolation from the then available 35 years of Anchorage weather data, the maximum number of degree days below 20°F (-7°C) with a probability of one per 100 years was determined to be 1,050 days. By correlation with available ice growth data, the 100-year ice design thickness of 42 in. (1.1 m) was established. Pressure ridges, formed by rafting (stacking up of ice floes), could increase this thickness. It was assumed, however, that most rafting occurs when the ice is thin and would not appreciably increase the ice thickness. The API RP 2N does not agree with this assumption and recommends that the design ice thickness be based on rafted ice.

Failure of the ice against the platform legs occurs from tension cracks or by direct compression. Since ice is stronger in compression than in tension, the design must be based on the compressive strength of the ice. The compressive strength of ice, however, was, and is, difficult to determine, since it is a function of a number of variables including the ice formation temperature, the thickness of the ice, the brine volume and the rate of loading. Both field and laboratory tests on ice samples were conducted at the time by Peyton\(^7\) under varying conditions. These tests indicated a maximum compressive strength, under laboratory conditions, of about 550 psi (3.8 MPa) for Cook Inlet ice. Field measurements established a shape or force coefficient of .55 for the relationship between the unconfined compressive strength of laboratory ice and the compressive strength of field ice. The API Recommended Practice recommends the same force factor and defines it as the product of the indentation and the contact factors.

Another company\(^1\) used a much lower ice strength, but assumed that the maximum load on the platform would be from pressure ridges. The resulting design loading condition is not much different from the previously described maximum loading condition.
Several of the platforms were instrumented with strain gauges to measure stresses during ice loading. Little useful data was obtained from these measurement programs because ice conditions in the Inlet were quite mild when these programs were active.  

3. DESIGN

3.1 Platform Types

Fifteen tower type platforms have been installed in Cook Inlet, see Table 1. Of these, 12 are four-legged towers, two are three-legged, and one structure, the monopod, see Figure 3, is a single legged tower.

3.2 Design Loads

The environmental and operational forces acting on a typical four-legged Cook Inlet platform, see Figure 4, are shown in Figure 5. Critical design loading is a combination of the maximum thickness ice hitting all four legs simultaneously at the highest tide elevation and with maximum drilling and operational vertical loads applied. As shown on Figure 5, this loading condition produces a lateral load of 10,000 kips (45 MN) and a vertical load of some 10,500 kips (47 MN). Although with current design practices a higher earthquake design loading would be used than shown on Figure 5, the forces imposed by an earthquake, when compared with the ice forces, are relatively small and do not govern the design.

3.3 Fatigue

When the ice crushes against the platform structures, the dynamic loading creates, depending upon velocity of the ice sheet, either a ratcheting motion or a vibration of the structure. Model tests were performed on a 1/4 scale model of a joint of one platform to evaluate the effect of this fatigue loading on allowable stresses and the estimated life of the structures. This effect turned out to be small and did not reduce the allowable stresses significantly. The fatigue life of the joint, based on the Inlet conditions, was estimated to range between 20 and 50 years. This does point out, however, the need to perform periodic underwater surveys of these platforms to inspect critical joints for any evidence of cracks.

3.4 Corrosion

Without protective measures there is severe corrosion of steel structures in Cook Inlet. Rates in the order of 35 mils/year (0.9 mm/yr), accompanied by significant pitting, were measured during the early years. This high corrosion rate is due, in part, to the high oxygen content of the fast moving, turbulent water. There is no marine growth on the structures which would otherwise tend to provide some protection from corrosion. In addition, erosion of the steel surfaces results from the high concentration of silt in the water and, during the winter, from the crushing ice floes.
During heavy ice conditions the platform legs through the ice zone are continuously polished to a bright metal finish.

As a precaution, and because there were significant questions whether or not a cathodic protection system could minimize or stop the corrosion in this environment, a corrosion allowance varying from 0.5 inch to 0.7 inch (13 mm to 18 mm) in the form of extra wall thickness or doubler plates was incorporated on most platforms during fabrication on the legs through the ice zone.\textsuperscript{3} On some of the earlier platforms where this had not been done, an external wrap was added to the legs to provide the additional protection.

Difficulties were experienced during the early years with the cathodic protection systems, partly because the anodes had not been attached securely to the legs, but mostly because the electrical current density requirement had been grossly underestimated. Once this was recognized, a number of anode sleds were installed adjacent to and under most of the platforms during the period from 1969 through 1974.\textsuperscript{11} With these systems the current density was increased from the original 25 milliamps per square foot (270 ma/m\textsuperscript{2}) to a range of 100 - 130 ma/sq.ft (1100 to 1400 ma/m\textsuperscript{2}). Much to the relief of everyone concerned this higher current density resulted in the deposition of a calcareous scale on the platform members and provided the desired protection. Recent inspections on the platforms indicate a virtually complete absence of corrosion.

4. FABRICATION

4.1 Fabrication Locations

Most of the platform tower structures, see Figure 6, were fabricated on the U.S. West Coast and towed to Cook Inlet. Three of the structures, including the most recent platform, were fabricated in Japan.

4.2 Low Temperature Steel

One of the concerns in the design of these platforms was the low temperature to which these structures would be exposed during the winter months. These temperatures, down to \(-40^\circ\text{F} (-40^\circ\text{C})\), could result in brittle fracture problems with the steels normally used for platform fabrication. This concern was further compounded by the fact that the tower type platforms do not have the redundancy of the template type structures.

To alleviate this potential problem the critical areas of the platforms, i.e. the main structural, above water, members, were fabricated from ASTM A-537 low-temperature steels. These are low-alloy steels made to fine grain practice with a yield strength of 50,000 to 60,000 psi (345 to 415 MPa). Two grades were used. ASTM A-537 Class I steel is heat treated by normalizing and has a transverse Charpy V-notch impact property of 30 ft-lbs (40 J) at a temperature of 0\(^\circ\text{F} (-18^\circ\text{C})\). Class II steel is
heat treated by quenching and tempering and has an impact property of 25 ft-lbs (34 J) at -40°F (-40°C).

Since residual stresses can play an important part in the initiation of brittle failure, the joint sections of several of the platforms were stress relieved after fabrication.

5. INSTALLATION

Timing of all construction work in Cook Inlet was, and is, very critical because of the high tides and associated high current velocity. This requires that all critical operations be performed in the relatively short period of slack tide as the current changes direction.12,13,14,15

The upending of these platform towers in the Inlet is a rather suspenseful operation. The bulky and massive structures are difficult to anchor in the high velocity currents. If something goes wrong the currents will carry the structure away from the site. This actually did happen during the upending of one structure and it is located about one mile distant from its originally intended location.

The entire sequence of a typical upending operation is depicted in Figure 7. The operation is performed at high tide to have maximum water depth available during the upending movement and to prevent the lowermost legs from touching the bottom prematurely. This entire operation must be completed in a time span of about 30 minutes.

The decks for most of the platforms were prefabricated on the U.S. West Coast with only a few fabricated in Japan. To reduce expensive derrick barge time in the Inlet, several were prefabricated as modules that were completely equipped and ready to operate. This, incidentally, was the first use of modules anywhere in the world.

6. MAINTENANCE

6.1 Underwater Inspection

A thorough underwater inspection is performed approximately once every five years on most of the platforms in the Inlet.16 These inspections include ultrasonic thickness measurements, verification of the cathodic protection potentials and examination of critical welds.

Because of the environmental conditions in the Inlet these inspections are time consuming and take an average of about three weeks. The diving operations can only be conducted during the tide changes, and the actual working time during each slack tide for the divers ranges from 35 to 40 minutes. Because visibility is essentially nil, divers must work by touch only.
6.2 Special Techniques

Several special techniques were developed to assist these inspection operations. These include the use of both still and video cameras mounted in a clear plexiglass box which has clear water flushing through it, and the use of underwater work scaffolds for divers to stand on while they are doing water blasting or photographic work. High pressure water blasting is used to clean welds and other areas to be inspected. Water pressures of 6 to 7000 psi (41 to 48 MPa) are needed to remove the heavy calcareous coating.

The remaining wall thickness of submerged platform members is determined by divers using hand held ultrasonic thickness measurement probes and with the read outs recorded on the surface using a multiple reflection oscilloscope. Best results are obtained on surfaces that have been cleaned by water blasting.

Critical welds and joints on the underwater portion of the structure that are subject to fatigue loading are inspected for cracks by first cleaning them with the water jets and then taking close-up detail photographs. As shown in Figure 9, excellent photographs can be obtained when using the special camera equipment mentioned earlier.

Verification of the underwater cathodic protection potential of the platform is performed by divers using a hand held half cell.

6.3 Inspection Results

Results from the more recent inspections indicate that the cathodic protection systems now in place on the platforms are adequately controlling corrosion. Little or no corrosion has occurred since the improved cathodic protection systems were installed following the alarming corrosion rates reported during the early years.

Apart from the loss of a horizontal member on one of the platforms, see below, there are no reports of structural damage to the structures. Divers have reported dents in some of the underwater members which were probably caused by ice collisions. None of these dents, however, were of the magnitude that they would affect the structural capability of the member.

6.4 Underwater Repairs

During the past twenty years there has only been one known instance of damage to a platform from ice loading. During the 1970-1971 winter a small ice floe became trapped between the underwater braces of one of the platforms during a very low tide. Smaller ice pieces subsequently froze to the trapped ice mass. On the following incoming tide the ice mass could no longer move freely through the platform and the piled ice sheared off a 6 ft (1.8 m) diameter horizontal member located 10 ft (3 m) below the waterline. Although the loss of this member did not affect the structural integrity of the platform, it was replaced the following summer.
7. CONCLUSIONS

The design criteria and methods that were developed some twenty years ago for the construction of platforms in Cook Inlet have proven to be effective and successful in this harsh environment. The subsequent installation of an improved cathodic protection system has arrested significant corrosion and, based on recent underwater inspections, the platforms can be expected to last the remaining economic life of the underlying reserves with a high degree of confidence.

8. REFERENCES


Table 1. Cook Inlet platforms listed by installation year.

<table>
<thead>
<tr>
<th>Year</th>
<th>Platform Name</th>
<th>Operator</th>
<th>Field Name</th>
<th>Platform type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1964</td>
<td>Platform A</td>
<td>Shell</td>
<td>Middle Ground Shoal</td>
<td>Four legs</td>
</tr>
<tr>
<td>1965</td>
<td>Baker</td>
<td>Amoco</td>
<td>Middle Ground Shoal</td>
<td>Four legs</td>
</tr>
<tr>
<td>1966</td>
<td>Granite Point</td>
<td>Unocal</td>
<td>Granite Point</td>
<td>Four legs</td>
</tr>
<tr>
<td>1966</td>
<td>Monopod</td>
<td>Unocal</td>
<td>Trading Bay</td>
<td>Monopod</td>
</tr>
<tr>
<td>1966</td>
<td>Anna</td>
<td>Amoco</td>
<td>Granite Point</td>
<td>Four legs</td>
</tr>
<tr>
<td>1966</td>
<td>Bruce</td>
<td>Amoco</td>
<td>Granite Point</td>
<td>Four legs</td>
</tr>
<tr>
<td>1966</td>
<td>Dillon</td>
<td>Amoco</td>
<td>Middle Ground Shoal</td>
<td>Four legs</td>
</tr>
<tr>
<td>1967</td>
<td>Platform C</td>
<td>Shell</td>
<td>Middle Ground Shoal</td>
<td>Four legs</td>
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<tr>
<td>1967</td>
<td>King Salmon</td>
<td>Arco</td>
<td>McArthur River</td>
<td>Four legs</td>
</tr>
<tr>
<td>1967</td>
<td>Grayling</td>
<td>Unocal</td>
<td>McArthur River</td>
<td>Four legs</td>
</tr>
<tr>
<td>1967</td>
<td>Dolly Varden</td>
<td>Marathon</td>
<td>McArthur River</td>
<td>Four legs</td>
</tr>
<tr>
<td>1968</td>
<td>Platform A</td>
<td>Phillips</td>
<td>North Cook Inlet</td>
<td>Four legs</td>
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<td>TS-A</td>
<td>Unocal</td>
<td>Trading Bay</td>
<td>Three legs</td>
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<tr>
<td>1968</td>
<td>Spark</td>
<td>Marathon</td>
<td>Trading Bay</td>
<td>Three legs</td>
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<tr>
<td>1986</td>
<td>Steelhead</td>
<td>Marathon</td>
<td>McArthur River</td>
<td>Four legs</td>
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Table 2. Ice design criteria for Cook Inlet platforms.

<table>
<thead>
<tr>
<th></th>
<th>Original Design Criteria</th>
<th>API RP 2N Design Criteria</th>
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<tbody>
<tr>
<td>Design ice thickness</td>
<td>3.5 ft (1.1 m)</td>
<td>2-3 ft (0.6-0.9 m)</td>
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<tr>
<td>Rafted ice</td>
<td>NA</td>
<td>4-5 ft (1.2-1.5 m)</td>
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<td>Unconfined compressive</td>
<td>550 psi (3.8 MPa)</td>
<td>500-600 psi (3.4-4.1 MPa)</td>
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<td>Shape factor</td>
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<td>Crushing ice pressure</td>
<td>300 psi (2.1 MPa)</td>
<td>275-330 psi (1.9-2.3 MPa)</td>
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<tr>
<td>Load condition</td>
<td>All four legs</td>
<td>Three legs</td>
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<tr>
<td>Maximum load (15.5 ft diameter legs)</td>
<td>9400 kips (42 MN)</td>
<td>9000 kips (40 MN)</td>
</tr>
</tbody>
</table>
Figure 1. Map of Alaska showing Cook Inlet.

Figure 2. Area of oil activity in upper Cook Inlet.

Figure 3. Monopod platform in the Trading Bay field.

Figure 4. Platform C in moderate ice cover.
Figure 5. Design loads on a typical tower platform in Cook Inlet.

Figure 6. Completed tower in the assembly yard.

Figure 7. Typical tower upending sequence.

Figure 8. Underwater photograph of a weld on a Cook Inlet platform.
DATA COLLECTION FOR DESIGN
THE ALASKAN EXPERIENCE

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ABSTRACT

The state of Alaska has data needs similar to those of the rest of the coastlines of the United States. The difference is that most of the state's 50,000 km of coastline are remote, often inaccessible. It is the remote nature of Alaska that creates a dilemma for coastal planners and designers; there is no information upon which to design. A program to collect needed wind and wave data was begun in 1982, but a combination of the vagaries of nature and the economy have had their impact. The mixed successes of the program to date have been lessons well learned and have been used to refine the effort and produce the multi-faceted program that now exists.

1. INTRODUCTION

Alaska, the largest and northern-most of the 50 United States, is nearly one-fifth the size of the 48 continental United States (Figure 1). Its 50,000 km of shoreline is the longest in the country. While much of that coastline is uninhabited, communities relying on the sea for their livelihood dot each of the state's diverse coasts. The remoteness of the communities, their geographic diversity, and the dearth of environmental data combine to produce one of the most complex design problems facing coastal engineers in the country.

The climate in Alaska varies from temperate and ocean-moderated in the area known as Southeast (that portion of the state that lies along the Gulf of Alaska) to arctic. The variability of the coastal areas is as dramatic as that of the climate. Tides, for example, range from .5 m along the Arctic coast to nearly 15 m in upper Cook Inlet near Anchorage. Strong
tidal currents are associated with the larger tidal ranges. The wave climate varies from the short period waves locally generated among the islands of Southeast Alaska to the depth-limited waves along the shallows of Norton Sound and the pounding Pacific surf along the Aleutian Islands. There are also many different types of shorelines found in Alaska. There are steep, rocky, fjord-like coastlines with bays and inlets; sandy beaches and large shallow bays, sand spits, and barrier islands; and mud flats. Beach materials vary from large cobbles and rocks to fine silt.

With such diversity in the design conditions, coastal planners and engineers need detailed, site-specific information to plan for and design their coastal projects, whether they be for shore protection or navigation. Because that information does not exist, the Alaska Coastal Data Collection Program was created in 1982.

2. ALASKA COASTAL DATA COLLECTION PROGRAM - THE PAST

In July of 1982, the US Army Corps of Engineers and the Alaska Department of Transportation and Public Facilities signed a cooperative agreement to initiate the Alaska Coastal Data Collection Program. The program had multiple goals, including the collection of field data, principally wind and wave data, for use by either party; development of instrumentation and telemetry suitable for the Alaskan environment; and archival of the data collected at a central location for ready retrieval as public information. The program plan also identified sites where data collection would be made over a five year period. This list of sites to be monitored was updated each year. Figure 2 shows an early list of sites. Many of these sites
have yet to be monitored, although two of the most successful data collection efforts were those at Kodiak and Homer.

Data collection was actually conducted by personnel from the Corps of Engineers' Alaska District with assistance from the Coastal Engineering Research Center located at the US Army Engineer Waterways Experiment Station. Conduct of the program is best described through an example, that of the data collection effort at Kodiak, the first station established.

Configuration of the program's data collection system was originally based on the use of "meteor burst" technology (Meteor Burst Communications Corporation, 1980) for system status reports. Data were actually recorded on magnetic tape on site, but the use of meteor burst allowed status checks to be performed daily. The layout of instrumentation and the shore station is shown in Figure 3 and the schematic of the system in Figure 4.

All of the sites instrumented in the early years of the program were configured similarly to that shown for Kodiak. The system consists of a master station located in the Alaska District offices in Anchorage and a shore or base station at the remote site. The remote location of most sites and poor quality of telephone transmissions required the use of on site data collection. A need to monitor the health of the instrumentation dictated the use of meteor burst for status checks through the receipt of summaries of system operation. Meteor burst uses meteor trails in the upper atmosphere as the medium from which data transmissions from remote sites are reflected to the master station. Use of meteor burst allows short data messages to be transmitted large distances without the use of satellites or telephones. It is an effective and inexpensive method of indicating system status, insuring that system failures are identified.
Figure 3: Kodiak instrumentation and shore station

Figure 4: Kodiak data collection and telemetry system

quickly so that repairs might be made expeditiously and data gaps might be as short as possible.

Most early data collection sites were located with deep water close to shore. Wave gages used were, therefore, those which could best measure wave height and period in deep water. Datawell by Waverider buoys were deployed at several sites, including Kodiak. Typically, two buoys were deployed to identify the transformation of waves from offshore to near to the project site. An anemometer was also deployed at each site. Each of the gages transmitted raw data to the shore station where it was stored on
magnetic tape. At first, 9-track tapes recorders were used, but these were replaced with cassette systems which proved more reliable and easier to maintain. Tapes were changed and mailed to Anchorage every three months or so. Daily summaries were automatically transmitted to the master station. Systems of this nature were deployed at Kodiak, Homer (Figure 5), and Akutan.

![Figure 5: Homer data collection and shore station](image)

Two other systems were utilized during the early stages of the program. To measure short period, locally generated waves in very deep water near Whittier, a spar buoy was deployed. The buoy was designed to record in situ, so meteor burst was not used for data checks of the wave data. At Nome, there was a particular need for directional nearshore data. For that site, a Sea Data, Inc. 635-9 Puv gage was deployed for the limited ice free season. Again, data were collected and recorded in situ. Wind data were collected at both sites as well.

Several problems were encountered during the early days of the program. Each of these has been overcome, some through changes in hardware and some through operational changes. One problem, already mentioned, was the hardware problem associated with the use of 9-track tape drives. These were fairly delicate, making them susceptible to failure in the often marginal protection offered at the shore station locations. The process of changing tapes also proved to be a bit complicated for some of the volunteers who watched over the shore stations. A change to much simpler cassette systems proved an excellent solution.

Meteor burst, while allowing daily status checks under most conditions, was not completely reliable. During those periods of the year when meteor
trails become scarce, the system would have trouble establishing a connection. Status checks would not be received for days at a time, causing concern that there had been a system failure. Patience, albeit uneasy, was required when meteor burst communications could not be established. An unnecessary maintenance trip was very costly to the program, so every effort had to be made to insure that there was actually a problem before a trip was made.

Avoiding complex equipment was a lesson slowly learned. The data collection effort at Nome was unfortunately delayed because of a desire to have the site report through meteor burst just as the other sites did. The system initially installed used a Puv connected via a data cable to a transmitter in a buoy. Data were transmitted to a shore station where they were stored on tape and system status transmitted to Anchorage by meteor burst. The system was expensive and complicated, and no data were ever obtained. Hardware and software problems hounded the effort, and, eventually, the system was damaged by a vessel, recovered, and salvaged. Deployment of the much simpler Sea Data, Inc. gage proved successful. With the experience at Nome, an important lesson was learned. In Alaska, more so than on other of the US coasts, simplicity in instrumentation is a key to success.

The most important lesson learned, though, was the level of planning and supervision necessary to insure the success of data collection in remote areas. The most dramatic example is the unsuccessful attempt to collect data at Akutan in the Aleutian Islands (Figure 2). Akutan is nearly inaccessible. It is reached either by boat or float plane only. The equipment to be used was transported by the US Coast Guard to the site. Although it had been agreed that the equipment, including the shore station, would be carried in the ship's hold, it arrived at Akutan on deck, having survived passage through several squalls. The equipment suffered from exposure to both fresh and salt water. District personnel attempted to clean the shore station, but its ultimate failure was attributed to its exposure. Problems at Akutan were exacerbated by the extreme remoteness of the site. The shore station was housed in a cell of the local jail, a facility that was not always heated. Power was provided by the local generator, equipment that was prone to fail for as much as a day at a time. Backup power for the shore station was good for only four hours, so gaps in data collection occurred as a result of power failures on shore. Finally, access to the site was difficult. Once there, a weather change could isolate a crew for days. On one occasion, a crew lived for three days on king crab dropped on a dock by a fisherman. Although quite tasty, three days of king crab can become quite tiresome. The experience at Akutan showed that it is probably
necessary to supervise the transport of all equipment and that each station needs to be entirely independent of local facilities.

3. ALASKA COASTAL DATA COLLECTION PROGRAM - THE PRESENT

For several years, the program produced results published in periodic data reports. Then oil prices dropped dramatically, and Alaska's ability to support the program was greatly diminished. Without the income from oil produced within its boundaries, the state had to eliminate many programs. Data collection, it was decided, would be approached on a as needed basis. But the impact on the Alaskan economy was widespread. Many other projects, including ones with Corps of Engineers involvement, were cancelled, further reducing the funding base for the data collection program. The sources of funds for the program had been the state, Corps projects, and Corps research efforts. All but the research funds, 15% or so of the total, were drastically reduced. The Alaska Coastal Data Collection Program had reached its doldrums.

Data collection has continued at Homer and has been resumed at Kodiak in support of projects at those sites. To reduce reliance on local facilities, two Waveriders have been converted to report via GOES. These buoys are being tested at Homer. Work is progressing on an inexpensive, ARGOS-reporting buoy, now that the decline of the value of the dollar has made the Waverider considerably more expensive. The program has not stagnated, though. Considerable data are collected every year in Alaska, principally by the Corps of Engineers, the state, and oil companies. Much of the oil company data is proprietary, so it may be unavailable. A new approach within the program is to actively pursue all data collected in Alaska. A new agreement is being developed to include this activity. It is intended that the University of Alaska Arctic Environmental Information Data Center look for, acquire, and archive these data. The center already has considerable historical data and has developed many of the contacts needed for an effort of this nature to be successful. As the data are assembled, they will be archived by the center, which will regularly report on what data are available.

4. ALASKA COASTAL DATA COLLECTION PROGRAM - THE FUTURE

While the effort to acquire existing data and to establish an archive for all data collected is the current emphasis of the program, new commitments have been made to the acquisition of the data so important to design. Principle funding for coastal data collection within the Corps comes from
the Coastal Field Data Collection Program. The intent of that program is to acquire the long-term, regional data needed for planning and design. Recently, that goal was reaffirmed and a commitment was made to provide the level of funding needed to accomplish the goal in a reasonable amount of time. That increased level of funding will allow for the collection of data in support of the efforts of the Alaska District. So, the establishment of an archive will be accompanied by the revitalization of field data collection efforts within the program.

5. CONCLUSIONS

Coastal planners and engineers in Alaska were faced with a mammoth task. They had to design difficult projects without the data needed in the design equations. The Alaska Coastal Data Collection Program was initiated to provide the data they needed. In its early stages, the program was a learning process, teaching participants important lessons about collecting data in a remote, often hostile environment. The most important lessons learned included the need for simplicity in the instrumentation used, for self-sufficiency in operation, and for planning for and supervising the details of the installation process. The program, as it has evolved, is one that will satisfy the needs of professionals working in the coastal zone in the last frontier of the United States.

6. ACKNOWLEDGMENT

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7. REFERENCES


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ANALYSIS AND INTERPRETATION OF AN AIRBORNE SYNTHETIC APERTURE RADAR IMAGE OF "HOBSON'S CHOICE" ICE ISLAND

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ABSTRACT

The most extreme ice features in the Arctic Ocean are ice islands or tabular icebergs. The largest ice island known today is "Hobson's Choice" Ice Island. An airborne synthetic aperture radar image of "Hobson's Choice" obtained in February 1988 is examined to determine the SAR characteristics of the ice island and changes that have occurred since it calved in 1982-83 from the East Ward Hunt Ice Shelf. The ice island has three ice components: 1) an area of shelf ice with a distinctive ribbed texture of lighter and darker grey tones arising from the undulating topography of linear hummocks and depressions; 2) an area of multiyear landfast sea ice (MLSI) that was originally attached to the front of the ice shelf and which has remained an integral part of the ice island since the calving; 3) an area of consolidated multiyear pack ice (MYP1) that has become attached to the ice island since the calving. The MLSI-MYP1 returns are darker than the shelf ice returns, due to greater dielectric losses and reduced returns at the radar. The ice island has maximum dimensions of 5.7 km by 8.7 km and it is estimated that the addition of the MYP1 has increased the ice island mass by 6% to 7.4 x 10^{11} kg, and the area to almost 34 km^2. An increase in ice island size by the addition of pack ice has not been documented previously. The distinctive ribbed texture of the shelf ice component, plus the size and angular shape of the ice island, distinguishes it from the surrounding smaller, rounded pack ice floes. The data indicate the potential for the use of airborne and/or satellite SAR for the detection and tracking of ice islands in the Arctic Ocean. This capability is important for the planning and implementation of the exploration and development of offshore hydrocarbon resources in the coastal waters of the Beaufort Sea and Chukchi Sea.

1. INTRODUCTION

Ice islands are tabular icebergs that calve periodically from the ice shelves located on the north coast of Ellesmere Island, N.W.T., Canada (Fig. 1). Ice islands vary in size from a few tens of metres across to as much as 30 km across, and they exceed 40 m thickness (Jeffries et
al., 1988a). Once they break off an ice shelf, ice islands become embedded in the pack ice and have been known to drift around the Arctic Ocean in the Beaufort Gyre for over 35 years. e.g. ice island T-3 (Sackinger and Yan, 1987). Because of their size and large-scale drift patterns, ice islands are recognized as a significant hazard to the exploration and development of offshore hydrocarbon resources in the coastal waters of the Beaufort and Chukchi Seas (IAARPC, 1987). Ice islands also are occasionally found in the inter-island channels of the Canadian Arctic Archipelago (cf. Koenig et al., 1952), where they are now recognized as a potential hazard to shipping (Personal communication, Pietro de Bastiani, Canarctic Shipping Company Limited).

The most recent ice island calving occurred in 1982-83 when at least eight ice islands broke off the East Ward Hunt Ice Shelf (Fig. 1) (Jeffries and Serson, 1983; Jeffries et al., 1988a). Since then a total of 32-34 ice islands have been found at the Arctic Ocean margin adjacent to Ellesmere Island and Axel Heiberg Island (Fig. 1) (Jeffries et al., 1988a). The largest of these ice islands is known as "Hobson's" Ice Island or "Hobson's Choice" Ice Island (hereafter referred to as Hobson's Choice) and is now the site of a research station operated by the Polar Continental Shelf Project (PCSP, Canada). At the time of the calving this ice island had a mean thickness of 42.5 m, an area of 26 km² and an estimated mass slightly exceeding 7 x 10¹¹ kg (Jeffries et al., 1988a). Since 1983, studies of Hobson's Choice have included: 1) measurement and analysis of patterns, dynamics and probabilities of ice island motion (Sackinger and Yan, 1987; Sackinger and Tippens, 1988; Li et al., 1988; Sackinger et al., 1989; Li et al., 1989); and, 2) ice core studies of the physical-structural-mechanical properties of ice island shelf ice (Jeffries et al., 1988a; Frederking et al., 1988) and the structure and growth history of the East Ward Hunt Ice Shelf (Jeffries et al., 1988b).

For the studies described in the previous paragraph incidental use was made of side-looking airborne radar (SLAR) images for counting the number and the size of ice islands (Jeffries, 1987; Jeffries et al., 1988a). Since the 1982-83 calving the ice islands also have been imaged
twice by airborne synthetic aperture radar (SAR). The imagery from the first occasion (December 1984) is not yet public. Imagery from the second occasion (February 1988) has been made available to assist us in our ice island studies. In this paper the results of the analysis of the February 1988 airborne SAR image of Hobson's Choice are presented, and changes in its area and mass in the five years since it calved are discussed.

2. IMAGE ACQUISITION

A radar image can be constructed by recording the intensity of microwave energy reflected or scattered from each resolution cell of a target scene and received by the antenna. The intensity or brightness of an individual resolution cell is related to backscattered energy; more scattering will cause a brighter or stronger return. The return signal is affected by the surface roughness, orientation, slope and complex dielectric constant of the target (MacDonald and Waite, 1973). The intensity of the return is also a function of incidence angle, polarization and frequency. To achieve high resolution a large antenna is required and the term 'synthetic aperture radar' refers to the well-known technique for moving sources in which digital signal processing is used to numerically (synthetically) create a much larger effective antenna area than would be possible from the physical size of the antenna. The high resolution capability of SAR is supplemented by its capacity to operate regardless of the weather, the time of day, or the time of year; an advantage of the microwave spectrum and a strong, active source, compared to the visible spectrum or passive microwave remote sensing.

The data used for this study of SAR detection and characterization of Hobson's Choice is X-band (30 mm wavelength), HH-polarized SAR data, originally presented to us as an image with a scale of 1:300,000. The data was obtained on 19 February 1988 from an altitude of 9450 m (31,000 feet) when the ice island was located at 79.98°N, 106.64°W (Argos buoy data), about 80 km NNW of Cape Isachsen, Ellef Ringnes Island (Fig. 1). The image is part of an extensive SAR data archive collected for the Canadian Arctic Marine Ice Atlas using the STAR-2 SAR system operated by Intera Technologies Ltd. Interpretation of the image is supplemented by field observations made in fall 1985, spring 1986 and spring 1987.

3. SAR CHARACTERISTICS OF HOBSON'S CHOICE

The original 1:300,000 scale SAR image is shown in Figure 2. Hobson's Choice is quite easily identified as an approximately diamond-shaped ice mass surrounded by pack ice floes and pressure ridges. The pack ice floes are somewhat smaller and have more rounded shapes than the ice island. The generally dark returns from the floes contrast sharply with the many bright returns from the pressure ridges within and at the boundaries of the floes. In addition to Hobson's Choice there are ten other ice islands in the image (Jeffries and Sackinger, unpublished MS[a]). Some of the other ice islands can be identified quite easily, while others, as small as 0.15 km by 0.25 km, are less easily identified by the inexperienced SAR user who
Figure 2. 1:300,000 scale SAR image of ice islands located in pack ice about 80 km NNW of Ellef Ringnes Island, N.W.T. Hobson's Choice is the large ice feature visible in the lower left corner of the image. The top edge of the image is north and the radar illumination direction is from the right.

also is not familiar with ice islands. The ten smaller ice islands are outside the scope of this paper and will not be considered in detail, except to note that they belong to the group of 32-34 ice islands reported in this region by Jeffries et al. (1988a).

An enlargement of the image of Hobson's Choice is shown in Figure 3a. The ice island has three ice components (Fig. 3b): 1) a long, narrow piece of shelf ice with maximum dimensions of 2.4 km by 8.7 km; 2) along one long edge of the shelf ice there is a triangular area of consolidated multiyear pack ice (MYPI) with a maximum width of 1.65 km; and, 3) along the other long edge of the shelf ice there is an area of multiyear landfast sea ice (MLSI) that has MYPI attached to its outer margins, giving a maximum width of 1.65 km. The MLSI and MYPI have equally dark returns and each area has been mapped using a SLAR image taken in May 1983 when only MLSI was attached to the ice island. Both multiyear ice components are considered to have been integral parts of the ice island in February 1988; thus, the ice island had maximum dimensions of 5.7 km by 8.7 km. Note also that a small area of MYPI has become attached to one side of the ice island SLAR-2 (Figure 3a, 3b).  

The shelf ice component has a distinctive ribbed texture of lighter and darker returns (Figs. 2 and 3a). The lineaments in the radar image are related to the undulating surface topography of linear hummocks and depressions that are a characteristic feature of arctic ice shelves and ice islands (Koenig et al., 1952; Hattersley-Smith, 1957). On Hobson's Choice the tops of the hummocks are generally about 1-2 m higher than the bottoms of the depressions. The hummock
Figure 3a. Enlarged SAR image of Hobson's Choice. The circle encloses bright returns from
the buildings of the Polar Continental Shelf Project scientific research station. In the top right-
hand corner there is a smaller ice island; it is referred to as ice island SLAR-2 (Jeffries et al.
1988a) or ice island 83-2 (Jeffries and Sackinger, unpublished MS [a]) and is the second largest
ice island known today in the Arctic Ocean. The width of the image corresponds to a distance of
10 km.

Figure 3b. Ice components of Hobson's Choice and an idealized cross-sectional profile
of the ice island (insert). Although the boundary between the MLSI and MYPI
components is unclear in the SAR image (Fig. 3a), the extent of the narrow fringe of
MYPI was mapped by comparing a 1983 SLAR image of Hobson's Choice, when it was
comprised of shelf ice and MLSI only, with the 1988 SAR image. The ice components of ice
island SLAR-2/83-2 are also shown.
spacing on the ice island has not been measured directly, but at East Ward Hunt Ice Shelf the
mean hummock spacing on aerial photographs is 212 ± 42 m (Jeffries et al., in press). The
returns from the broad, curved crests of the hummocks are stronger on one side and weaker on
another, as the angle of incidence between the radar beam and the ice changes. The depressions
are of two types: 1) those which contained freshwater melt pools in summer 1987 and which
refroze in the winter to form a specularly-reflecting lake ice surface, with a resultant weak radar
return; 2) those which were formerly lakes, but from which the meltwater has suddenly drained
during previous summers, thus exposing the irregular surfaces of the former bottoms of the
melt-pools which cause more variable and stronger radar returns. Meltwater lakes have been
observed draining catastrophically off the edge of the ice island (Personal communication,

On average the shelf ice returns are brighter than the returns from the multiyear ice
components (Figs. 2 and 3a). The difference in returns can be attributed to both topography and
ice property differences. Previously it has been shown that the shelf ice component comprises
bubbly, granular fresh-water ice of very low d.c. conductivity (5.86 μS cm⁻¹) (Jeffries et al.,
1988a; 1988b; Frederking et al., 1988). On the other hand, although the sea ice conductivity has
yet to be measured, the ice must be more saline than the shelf ice, and because of the brine
entrapped in sea ice the dielectric losses are greater than in fresh-water ice and the resultant rapid
attenuation causes a reduced return at the radar (Sackinger and Byrd, 1973; Vant et al., 1974).

Unlike the textured shelf ice return, the returns from the multiyear ice components show little
texture (Fig. 3a). The shelf ice texture is related to large-scale topographic variations, but the
lack of texture in the multiyear ice returns does not imply an absence of significant topographic
variation. The multiyear ice components do have hummocky surfaces because they have
undergone several or many melt seasons. In the case of the MLSI the hummocks and
depressions have a linear appearance when viewed optically. On MLSI elsewhere the
hummocks are up to 1 m high and have a mean spacing of 67 ± 15 m (Jeffries et al., in press),
and when the radar illumination is normal to the undulations the MLSI shows a ribbed texture in
a SAR image (Jeffries and Sackinger, unpublished MS[b]). In the case of Hobson's Choice the
radar illumination direction is parallel to the MLSI undulations and there is reduced apparent
texture (Figs. 3a and 3b).

The brightest returns from the ice island occur at the outer margins of the shelf ice and the
multiyear ice. The edges of the ice island have two general forms: 1) many pressure ridges of
annual ice rubble built up along the margins, locally exceeding the height of the shelf ice
surface, i.e. >5 m; 2) a vertical ice cliff which, in the case of the shelf ice, can be up to 5 m high
with adjacent open water or thin, new ice. Occasional older pressure ridges that have survived
more than one summer are also observed at the ice island margin, but annual ice pressure ridges
are more common and probably the most common edge feature in the image (Fig 3a). Because
they have steep slopes, sharp corners and many voids, pressure ridges show up well in the
SAR image, presumably due to some combination of corner reflector and multiple scattering effects, plus specular reflection off flat facets. There is probably an ice cliff exposed at the broad, flat end of the shelf ice where a bright, linear return contrasts with an adjacent dark return (Figs. 3a and 3b). The planar, vertical cliff surfaces are thought to produce the bright returns, whereas the dark return is probably from newly-formed, lossy sea ice.

4. THE COMPONENTS OF HOBSON'S CHOICE AND AREA-MASS CHANGES

In May 1983, Hobson's Choice had an area of 26 km$^2$ and just two ice components; the shelf ice and the MLSI. The MLSI was attached to the front of the East Ward Hunt Ice Shelf at the time of calving (Jeffries, 1987; Jeffries et al., 1988a) and has remained attached to the shelf ice since then. By February 1988 the ice island had acquired a third component since the calving, i.e. the consolidated multiyear pack ice (MYPI). The total area of MYPI is 7.75 km$^2$; thus, the area of Hobson's Choice has increased by almost 30% to 33.75 km$^2$.

On the basis of known and assumed ice properties, and the thickness of the shelf ice and MLSI components, the original mass of the shelf ice was estimated to be 701.8 x 10$^6$ tonnes (Jeffries et al., 1988a). If density and thickness values are assumed for the MYPI, and if ice losses by melting of the shelf ice and the MLSI are taken into account, an estimate can be made of the mass of Hobson's Choice in February 1988.

According to observations and measurements of ice conditions in this region of the Arctic Ocean, by surface parties and submarines, the mean pack ice thickness is on the order of 5-6 m (Wadham, 1981; 1984; Bourke and Garrett, 1987). A thickness of 6 m is assumed for the MYPI, which is corroborated by a few measurements made in 1986. For the MLSI a bulk density of 910 kg m$^-3$ was assumed (Jeffries et al., 1988a) and the same value is assumed for the MYPI. The added mass of MYPI, therefore, is 42.3 x 10$^6$ tonnes.

Since the calving in 1982-83 there has been considerable summer ice loss from the surface of the ice island, including the complete drainage of many meltwater lakes. Detailed measurements of ice loss from the hummocks and the additional melting effects of relatively warm meltwater lakes have not been made, so estimates of the ice losses must be based on indirect methods. Summer ice surface lowering since 1983 has varied from almost zero to 0.6 m, with a trend to increasing annual losses as the ice island has drifted from 83°N to 79°N. By the end of summer 1988 the cumulative ice losses, as estimated by ice pedestals beneath buildings erected in fall 1984, were from 0.5 m to 1.5 m (Personal communications from Michael Schmidt, Geological Survey of Canada, and Harold Serson, Consultant). Possible ice losses by melting below the waterline are unknown, but may be neglected due to the cold water in these regions, even in summer. If it is assumed that surface ice losses since 1983 from the MLSI and the shelf ice amounted to 1.5 m, with most of the water flowing off the edge of the ice, then, the mass of ice lost by ablation is 3.5 x 10$^6$ tonnes. The addition of MYPI, therefore, has increased the mass of Hobson's Choice by almost 6% to 740.6 x 10$^6$ tonnes.
A highly idealized cross-sectional profile of the ice island is shown in Figure 3b. The diagram shows the average thicknesses of the MLSI and MYPI components as flat plates, without the pressure ridges that are found at the shelf ice-multyear ice boundaries and at the MLSI-MYPI boundary. Since the extra mass of the thicker deformed ice has not been taken into account, the above estimate of the mass of the ice island may be smaller than that which would be computed from an actual profile.

5. DISCUSSION AND CONCLUSION

With maximum dimensions of 5.7 km by 8.7 km, Hobson's Choice is the largest ice island in the Arctic Ocean at the present time (Jeffries et al., 1988a). It represents an interesting target for synthetic aperture radar imaging and was easily detected visually in the original 1:300,000 scale SAR image (Fig. 2). The most distinctive SAR characteristic of Hobson's Choice is the ribbed texture of the shelf ice return. A similar return is evident in SEASAT SAR images taken in 1978 of ice island T-3 (Fu and Holt, 1982), but those from Hobson's Choice are more distinctive. Smaller ice islands than Hobson's Choice have been detected in the 1:300,000 scale image (Figure 2), the smallest being 0.15 km by 0.25 km (Jeffries and Sackinger, unpublished MS[a]). However, for the casual user of SAR images at the 1:300,000 scale it has been suggested that ice islands with dimensions on the order of \( \geq 300-400 \) m will be the minimum size for confident visual detection (Jeffries and Sackinger, unpublished MS[a]).

In addition to the relatively thick shelf ice component, Hobson's Choice also includes extensive areas of somewhat thinner multiyear ice. The multiyear pack ice (MYPI) component is particularly interesting because it represents a means by which ice islands can increase their size as they drift in the Arctic Ocean. Ice island grounding on the sea-bed followed by disintegration into smaller pieces has been reported (Spedding, 1977), but an increase in the size of a drifting ice island by the addition of multiyear pack ice has not been documented previously. This indicates that ice island interactions with offshore structures can have multiyear ice in the zone of contact.

The first confirmed ice island sighting in the Arctic Ocean in 1946 was on an aircraft scanning radar followed by visual contact and observation (Koenig et al., 1952). The ice island was notable for its great size and a distinctive arrowhead shape. It is, therefore, somewhat ironic that, 40 years later, using a more sophisticated imaging radar, Hobson's Choice is also easily identified because of its greater size and more angular shape than the surrounding pack ice floes. Forty years ago ice islands were considered something of a novelty, as well as useful platforms for drifting Arctic Ocean research stations. Today, they still play an important role in Arctic Ocean research, but, with the advent of offshore petroleum development in the North they have assumed a new significance. Ice islands are relatively easy targets for SAR detection and observation, and a combination of airborne and satellite SAR probably represents the best means to obtain a census of ice islands in the Arctic Ocean. A SAR-based census of ice islands

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would provide essential data (numbers, locations, size, degradation and production rates) for
the planning and implementation of exploration and development of hydrocarbon resources in
coastal waters of the Beaufort Sea and Chukchi Sea.

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AIRBORNE SEA ICE THICKNESS SOUNDING

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ABSTRACT

Airborne remote measurement of sea ice thickness has been an elusive goal. Many sensing systems have been tried and evaluated, including impulse radar. All these systems were found to have limited capabilities at best. We are now evaluating airborne electromagnetic induction technology, which has long been used for mineral prospecting. Two field studies have been made in the Arctic. One study has been done using a relatively standard 7-m-long, 1/2-m-diameter helicopter-towed antenna, and one using a lighter down-sized antenna only 3 m long and 1/3 m in diameter. The airborne sea ice thickness sounding profiles obtained indicated that the thickness could be estimated but the resolution decreased as the ice became rough. This decrease was associated with the large footprint of the system, which effectively smoothed out the sea ice relief. However, it was found that the average ice thickness estimated by airborne electromagnetic sounding for a given flight track was in reasonable agreement with the average ice thickness determined by direct drill hole measurement. Examples of the ice thickness profiles obtained by airborne sounding and direct drill hole sounding are presented and compared. Future development of the airborne system is discussed.

1. INTRODUCTION

Fixed-frequency airborne electromagnetic (AEM) induction systems have been used for several decades in mineral exploration. The technology has now advanced to where more demanding sounding applications can be considered. Sea ice thickness and bathymetric sounding are two areas where AEM technology can, in principle, now be used successfully. In this method, a
tubular sensor platform (bird) is towed by a cable suspended from a helicopter. Fixed frequency transmit coils $T_x$ are located at one end of the bird and related receiver coils $R_x$ at the opposite end. When operated over sea ice, the transmit coils produce a primary electromagnetic field which induces eddy currents in the conductive sea water. These currents, in turn, produce a secondary electromagnetic field which is sensed by the receiving coil. The in-phase and quadrature phase of the secondary field, in ppm, relative to the primary field at the receiver coil are functions of the bird height above and the conductivity of the sea water. The phase data, along with frequency $T_x$ and $R_x$ coil spacing and orientation and bird pitch and roll sensor data, are then used to calculate an apparent sea water conductivity and bird height above the conductive surface (Kovacs, et al. 1987). At high frequencies, the conductivity of the sea ice will also influence the secondary field parameters, as will the sea bed when the depth of water under the ice cover is less than about two skin depths. A laser profilometer mounted in the bird measures the distance between the platform and the ice surface. Subtracting the AEM distance from the laser distance gives an estimate of the relative ice (or snow and ice) thickness.

Previously we reported on the use of a four-frequency (AEM) system for measuring sea ice thickness (Kovacs et al. 1987, Kovacs and Valleau 1987). This field program, undertaken in May 1985, verified the feasibility of using AEM sounding for the measurement of sea ice thickness and under-ice bathymetry using a relatively standard geophysical survey system. The AEM system consisted of a 7-m-long, 1/2-m-diameter bird. With internal support structure and electronics, tow cable and drag assembly, the bird weighed about 200 kg. Shipping this long bird to the Arctic proved very expensive and it was cumbersome to handle.

The field program revealed a number of areas where system performance improvements were needed. Among them were excessive system drift (in particular, nonlinear drift) and internal noise, poor resolution, slow sampling rates and analysis capability and the need for real time calibration.

To reduce the size and weight problem, a bird only 3 1/2 m long and 0.35 m in diameter having an all-up weight of about 150 kg was designed and fabricated by Geotech, Ltd. Using the spreader bar and drag skirt for scale, the relative size of the two birds can be seen in Figure 1. The small bird had three fixed frequencies of 0.8, 4.5 and 50 KHz with new low drift and low noise driver and receiver electronics. An improved data acquisition system was also used. This unit had much more dynamic range, with a 16- versus 12-bit A to D conversion module in the previous unit.
Figure 1. Standard size AEM bird (a) and new, shorter bird used in 1987 (b). The relative size difference can be observed by comparing the length of the two birds with the length of the drag skirt spreader bar, which is the same in both photos.

Mounted in the bird was a high resolution, 0.01-m accuracy laser profilometer. A global satellite positioning system was used to monitor flight line location and record the position of the sounding data. Field data analysis speed was increased through improved processing software and the use of a Micro VAX II minicomputer.

2. FIELD ACTIVITIES

The new AEM sounding system was tested in May 1987 off the Beaufort Sea coast of Alaska. Extensive ground truth information (snow and ice thickness, water depth, temperature and conductivity, and satellite position data) was collected at numerous sites over which AEM soundings would be made. The sites included both first-year and multi-year sea ice. The data collected at several of the sites are presented in this paper.
AEM system calibration was to have been achieved through the use of an internal calibration system. Suffice it to say that this "unique" device did not meet expectations. The AEM system was then calibrated using standard ferrite bar and external Q-coil techniques as employed when AEM systems are used for geophysical prospecting. In this technique, a known anomaly with equal in-phase and quadrature components is generated. These components are used to adjust the amplitude response of the system. However, this on-ground calibration method did not meet the accuracy required. Apparently, the very small secondary field reflected from the ground at the flight line calibration site biased the calibration. Therefore, calibration was accomplished by collecting AEM sounding over an area of level sea ice of uniform 1.45 m thickness and adjusting the appropriate system response to agree with that for the known bird height above the ice/water interface. If no component changes are made to the AEM system, this calibration is a stable parameter, and needs only to be done once; the system is then calibrated for any future survey activity.

Station K was located on first-year sea ice. The ice averaged 1.74 m thick and was blanketed with 0.10 m of snow for a total thickness of 1.84 m. Under-ice water depth was 8.85 m, and the water had a temperature of -1.7°C and a conductivity of 2.6 S/m. This site was sounded six different times on several different days. The AEM snow and ice (S-I) thickness determinations were 1.68, 1.84, 1.90, 1.96, 2.45 and 2.50 m. These average 2.06 m, or 12% higher than the measured value. Individually, the AEM S-I thicknesses varied from 9% below to 36% above the average drill hole measured value. Part of the spread is believed associated with nonlinear drift or an inability to obtain a good instrument zero reading due to a low cloud ceiling. A system zero reading is obtained by flying the bird to an altitude at which no secondary field is measured at the receiver coil from a conductive body (e.g. the sea water) and then noting the system response parameters. This procedure is done before and after a sounding run to obtain information on system drift, which is then removed from the AEM sounding data. In any event, this wide spread in the AEM S-I thicknesses is not acceptable and must be improved.

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<th>AEM sounding thickness (m)</th>
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<tr>
<td>K</td>
<td>1.84</td>
<td>2.50</td>
</tr>
<tr>
<td>L</td>
<td>1.93</td>
<td>2.24</td>
</tr>
<tr>
<td>M</td>
<td>1.95</td>
<td>2.45</td>
</tr>
<tr>
<td>N</td>
<td>1.03</td>
<td>0.79</td>
</tr>
<tr>
<td>O</td>
<td>0.94</td>
<td>0.83</td>
</tr>
</tbody>
</table>
Linear system drift can be dealt with when analyzing the AEM sounding data. Nonlinear drift cannot be satisfactorily accounted for. Nonlinear drift effects can be seen in the AEM S-I thickness data obtained at stations H through O located along an 18-km-long line laid out on first-year sea ice. Table 1 lists the average of four drill hole measured S-I thicknesses at each station versus the AEM-determined value. The AEM S-I thicknesses at the beginning of the flight line, at station H, were lower than the measured value. As the 10-minute flight progressed, the AEM S-I thicknesses gradually increased to where they exceeded the measured ones and then decreased. The time between zero readings was about 15 minutes. Again, the variation in the AEM-determined S-I thicknesses versus the measured values must be eliminated before AEM sounding of sea ice thickness can be considered a viable measurement technology.

Figure 2. Snow and ice thickness contour map of grid site on multi-year sea ice floe 1.
On a multi-year ice floe, a 50-m-wide by 450-m-long grid was laid out. The width was divided into 11 longitudinal lines, A through K, spaced 5 m apart. Lateral rows 5 m apart divided the grid into 91 distance-stations, 0 through 450. At the intersection of each row and line, the snow and ice thickness and the freeboard were determined by drill hole measurement. From these data, a snow-ice thickness contour map for the grid site was made (Figure 2). The purpose of the grid, and related drill hole measurements, was to ascertain whether the AEM-determined S-I thicknesses agreed with the measured values. In our previous study (Kovacs et al. 1987), we determined that the AEM footprint, or the area over which the integrated S-I thickness is estimated, ranges from one to two times the bird altitude. If the bird is flown 25 m above the surface, then the footprint is, as a first approximation, at least 25 m in diameter. Therefore, the average drill hole measured S-I thicknesses within an area of ice about the diameter of the AEM footprint would be required to assess the validity of the AEM S-I thickness determination.

The objective at the grid site was to fly down its center (Figure 3), sounding the S-I thickness and referring these measurements to the location of station markers placed on the surface. Common fiducial numbers recorded on the AEM data and the flight path video allowed for location-data cross correlation.

Figure 3. The grid area on multi-year sea ice floe 1. The snow trampled during drilling produced the outline shown. A dyed centerline can also be seen.

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Figure 4. Cross section of the grid site on floe 1 as constructed from the averaged drill hole measurements.

Figure 5. Average measured versus four AEM determined snow and ice thickness profiles along the grid on floe 1.

The average snow thickness, ice freeboard and keel draft along the length of the grid are given in Figure 4. The thinnest average S-I ice area was about 3 m thick, while the thickest areas were about 6 m thick.

Snow-ice thickness profiles for four flights flown down the grid are shown in Figure 5, along with the average drill hole measured S-I thickness. It is apparent that the AEM profiles follow the long period variation of the measured snow-ice thickness profile but not the short period undulations. As previously discussed, this is due to the averaging associated with the footprint area over which the ice thickness is being integrated as well as the use of a one-dimensional analytical model to characterize three-dimensional relief. It appears that short period thickness variations, which occur over distances of less than two or three times the bird height, will not be well defined, if defined at all, in the AEM sounding profiles.
While there is general agreement between the AEM and measured S-I thickness profiles in Figure 5, the profile for flight F1213 shows a gradual increase in thickness after a distance of about 310 m. Nonlinear system drift is again believed to be the problem.

The mean drill hole measured S-I thickness for the floe was 3.96 m with a standard deviation of ± 1.31 m. Similar values for Flights F1213, F131L, F131L0 and F14L7 are 4.27 m (± 1.09 m), 4.18 m (± 0.89 m), 4.09 m (± 0.92 m) and 4.11 m (± 0.88 m) respectively. All AEM mean S-I thickness flight line values are biased to the high side but are well within ten percent of the drill hole determination. This suggests that a properly designed and developed AEM system can provide useful information on the mean ice thickness of ice floes with relatively mild relief.

On another multi-year ice floe with more severe relief (Figure 6), a similar width but only 200-m-long grid was established. This floe, number 3, had a mean S-I thickness of 4.21 m with ± 1.54-m standard deviation as determined by drill hole measurement.

From three AEM flights made over this floe’s grid, we obtained mean S-I thicknesses and related standard deviations of 3.57 m (± 1.39 m), 4.30 m (± 1.23 m) and 4.91 m (± 1.14 m). In this case, the variation between the mean drill hole measured S-I thickness and the AEM determinations was about fifteen percent. This is a seven percent larger variation than for floe 1. Part of this additional variation is believed related to nonlinear drift as may be seen in Figure 7. For Flight F131L5, the AEM S-I thicknesses are lower than the measured ones at the beginning of the floe’s grid, at station-distance 0, but fall into somewhat better agreement at

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Figure 7. Average measured versus three AEM determined snow and ice thickness profiles along the grid on floe 3.

Figure 8. Cross section of first-year pressure ridge grid site as constructed from the averaged drill hole measurements.

the end of the overflight. For Flights 13L6 and 13L8, the direct versus remotely measured S-I thickness is in reasonably good agreement at the beginning of the grid but thicker S-I values occur in the area of the deep keel.

The AEM thickness profiles obtained along a grid established on first-year sea ice which included a 20-m-thick first-year pressure ridge (Figure 8) are shown in Figure 9. The most striking aspect of the AEM profiles is that they do not adequately define the thick ice of the ridge. As previously stated, because of the footprint size and the model constraints as well as the relatively steep-sided relief of the ridge keel, it is currently not possible to properly define such ice features with widths of 2 to 3 times the bird height. Considering that the thick ice area is less...
Figure 9. Average measured versus three AEM determined snow and ice thickness profiles along the grid at the first-year pressure ridge.

than 60 m wide and the bird was flown at about 23 m above the undeformed surface relief, the results shown in Figure 9 are not unexpected. The AEM S-I thicknesses do agree reasonably well with the measured thicknesses on either side of the ridge and do indicate the location of the thicker ridge ice. Smoothing of the relief in the area of the ridge is again associated with footprint size, ridge geometry and model constraints.

3. DISCUSSION

During the 1987 field study, major linear and nonlinear drift (as well as noise) problems were experienced which adversely affected the quality of the AEM data and made their interpretation difficult. As a result, it is appropriate to conclude that the specially designed Geotech Ltd. AEM system used did not represent a sufficiently mature technology for use in obtaining accurate measurements of sea ice thickness. This would especially be true if large area ice cover thickness distribution was desired for use in modeling ice pack dynamics or in assessing heat transfer from an ice-covered sea to the atmosphere. Nevertheless, the results of this and the 1985 field study (Kovacs et al. 1987, Kovacs and Valleeau 1987) indicate that the AEM sounding system could be used to find areas of thick and thin sea ice and to give an indication of the thickness. Such information may be useful in ship routing through ice-covered waters. However, the cost, complexity and non-real-time analysis and display of the data appear to make the current technology not very attractive for this use.

The above discussion is an expression of caution on the usefulness of AEM sea ice thickness sounding at this stage of its technological develop-
ment. On the optimistic side, we have reason to believe that AEM sounding of sea ice will evolve into a mature, user-friendly technology capable of providing accurate sea ice thickness data useful for many scientific and applied uses. In the near term, we envision a lighter-weight system with very stable electronics, high sampling rates, real time calibration, faster data processing and real time display of ice thickness. Indeed, we are currently addressing these areas in our development of a single-transmitter, wideband, time domain, helicopter-deployed electromagnetic sea ice thickness sounding system which should be flying in 1989. The use of artificial intelligence techniques may one day result in a very user-friendly system. Such techniques would include a data base against which the system would adjust for such aspects as flight elevation changes and would remove the need of a highly trained operator to initialize and monitor the system.

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5. ACKNOWLEDGMENTS

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WIND-GENERATED POLynyI OFF THE COASTS
OF BERING SEA ISLANDS

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ABSTRACT

The relationship of winds derived from mesoscale meteorological networks to polynya sizes and orientations was investigated. Defense Meteorological Satellite Program imagery was merged with atmospheric pressure network data from the Bering Sea for March 1988.

During the month, wind systems drove sea ice southward, creating and maintaining polynyai south of St. Lawrence, St. Matthew, and Nunivak Islands. Existing land stations, the deployment of a moored pressure buoy south of the ice edge, and a new automated weather station on St. Matthew Island have allowed the "creation" of mesonetworks that surround these lee-shore polynyai.

This analysis (rather than synoptic) has shown that polynya lengths and orientations can be simply related to the mesonet computed geostrophic winds. The typical time lag between the onset of a geostrophic wind and the appearance of "windsock" type tracking of the polynya is 24 hours.

1. INTRODUCTION

Undercast-free visible band satellite imagery of the ice-covered Bering Sea appearing in scientific literature over the past 15 years points to a very striking phenomenon. Lee shore polynyai are almost "always" present off the St. Lawrence, St. Matthew, and Nunivak Island south coasts. The relative openness of these polynyai and their resemblance to "windsocks" are unmistakable. Representative studies by Shapiro and Burns (1975), Cavalieri et al. (1983), Paluszkiewicz and Niebauer (1984), Reynolds et al. (1985), and Shapiro et al. (1988) show evidence of these features.

These latent heat polynyai (Smith, 1988) open and persist because sea
ice is removed as on a wind-driven conveyor belt almost as fast as it
forms. Apparently the combination of wind speed, air temperature, and
solar radiation in this area do not allow the polynyi to reach maturity
(polynya length ceases to increase) within a typical synoptic period of 5
days (Pease, 1987). Oceanic processes driven by brine rejection (Kozo,
1983) lead to density-induced current flow (Schumacher et al., 1983)
beneath the polynyi.

An initial study focusing only on wind effects has been launched to
relate mesoscale meteorological network (Kozo et al., 1987) data to
polynya orientation and length. The polynya information was taken from
Defense Meteorological Satellite Program (DMSP) Imagery obtained in March
1988. Existing land weather stations, a moored oceanic weather-buoy
below the southern limit of sea ice in the Bering Sea, and an automated
weather station on St. Matthew Island have allowed the implementation of
polynya-surrounding mesonets (Figure 1) for the above mentioned Bering
Sea Islands. Previous work (Kozo, 1984) has shown that synoptic analyses

Figure 1. Map of the Bering Sea shelf and basin (from Paluszkiewics and
Niebauer, 1984) showing the ice island polynyi (speckled triangles). The
St. Lawrence Island mesonet stations are Provideniya (A), Nome (B), and
St. Matthew Island (C). The St. Matthew Island mesonet stations are C,
Mekoryuk Airport (E) and Buoy 35 (D). The Nunivak Island mesonet
stations are E, St. Paul (F) and Bethel Airport (G). The 50 m, 100 m,
and 200 m (shelf break) isobaths define three hydrographic domains. The
coastal and slope current locations are shown by bold arrows.

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from the National Meteorological Center (NMC) are often insufficient to reproduce actual wind stresses at specified locations due to mesoscale effects and/or poor resolution. In addition, synoptic charts from the Bering Sea region during the study period did not have the detail necessary for precise predictions of winds at each of the three study islands on moderate to light wind days (See Figure 2).

![Figure 2. Surface atmosphere pressure chart showing the lack of detail in the area covered by the mesonets (dashed triangles). The arrows show that three different wind stress directions are predicted within nets A-B-C, C-D-E, and E-F-G for March 13, 1988.](image)

2. STUDY AREA

The eastern Bering Sea has a wide (~500 km), shallow (~170 m at the shelf break) continental shelf (Paluszkiwicz and Niebauer, 1984) just to the east and west of St. Lawrence Island (Figure 1), the northern flow is strong (~10-15 ms⁻¹) but south of St. Lawrence the mean flow is weak (~02-04 ms⁻¹), (Schumacher et al., 1983). In fact, the characteristic flow on the shelf is normally slow (< 02 ms⁻¹, Kinder and Schumacher, 1981). Three distinct hydrographic domains (Figure 1) are defined: (1) the coastal domain inshore of 50 m dominated by buoyancy driven flow (~01-03 ms⁻¹) contains the St. Lawrence Island and Nunivak Island polynya, (2) the middle domain between 50 m and 100 m (weak flow) contains the St. Matthew Island polynya, and (3) the outer domain between 100 m and the shelf break (weak flow). Seaward of the shelf break, the Bering slope current (Figure 1) flows at a speed of approximately ~1 ms⁻¹.
(Paluszkiewics and Niebauer, 1984). In essence, the available oceanographic data for the lee shore polynyi areas in this study indicate that sea ice drift will be dominated by wind systems.

During March 1988, there was a tendency for low pressure systems to propagate zonally across the southern Bering or northward across the Alaskan side of the Bering Sea. Both situations resulted in driving sea ice southward (Pease et al., 1982) creating and maintaining polynyi off the southern coasts of St. Lawrence, St. Matthew, and Nunivak Islands.

3. DATA AND ANALYSIS TECHNIQUES

3.1 Satellite Imagery

The polynyi size and ice motion data for March 1988 came from visible band DMSP satellite imagery. The net 24-hour ice motion was measured directly by tracking an ice edge location south of the study islands. The system resolution (designated LF, light fine) is .5 km. Displacements were determined by registration of images relative to adjacent topographic features. The estimated uncertainty is ±5 km.

3.2 Atmospheric Pressure, Temperature, and Geostrophic Winds

Sea level barometric pressure and temperature data were taken simultaneously from weather station combinations in the study area (Figure 1). The three mesonetworks used were:

1. Bukhta Provideniya (Russian) - Nome - St. Matthew Island (Buoy 17, automated station designator from the National Climatic Center (NCC)).
2. Buoy 17 - Buoy 35, a moored (57°N, 177.7°W), automated meteorological station; NCC collected the data) - Mekoryuk Airport.

Pressure and temperature data from first-order weather stations such as Nome, Bethel, St. Paul, have accuracies better than ±.25mb and ±1°C respectively. Provideniya and the buoys 17 and 35 are part of a global station network transmitting to the National Meteorological Center (NMC). Their accuracies are within the same limits. Mekoryuk Airport data are assumed to be close to the above limits since it has air traffic.

Geostrophic winds are computed from station pressure and temperature data for the above mentioned network combinations. The solution is best at the geometric center of each network which was chosen for its proximity to the study polynyi. The atmospheric flow is assumed to be in geostrophic balance. Using the station geometry as shown in Figure 1,
pressure can be represented as a function of latitude \( (\gamma) \) and longitude \( (\lambda) \) on a plane surface. The pressure gradient \( \nabla P \) can be computed and geostrophic velocity \( V_G \) can be calculated since the Coriolis parameter \( (f) \) is known and density \( (\rho) \) for dry air can be estimated from station temperatures (Kozo et al., 1987).

Station errors of \( \pm 1^\circ \)C in temperature can cause errors of \( .34\% \) in velocity magnitude since they affect \( \rho \) estimates. Errors of \( \pm .25 \) mb can cause maximum speed errors of \( \pm 1.5 \) ms\(^{-1} \) and direction errors greater than \( 15\% \) of full scale for wind speeds below 3 ms\(^{-1} \). Therefore, at wind speeds of 3 ms\(^{-1} \) or below, computed wind directions are not reliable.

3.3 Calculation of Ice Velocities

The conversion of geostrophic wind speed (see above) to 10 m wind speed \( (V_G) \) is \( .6V_G = V_S \) (Albright, 1980). The sea ice, free drift speed \( (V_I) \) used to estimate ice advection at the polynya edges is \( .03V_S = V_I \). This is an oceanographic "rule of thumb" (Csanady, 1984). Predicted polynya lengths given below are the product of \( V_I \) and the number of days (in seconds) that the wind blew in a given direction.

4. RESULTS AND DISCUSSION

4.1 St. Lawrence Island

Figure 3 shows a Bering Sea DMSP image from March 14, 1988. The apex of the triangular polynya to the lee of St. Lawrence Island lines up with the 170\(^\circ\)W meridian. The prior period (March 10-13, 1988) had an average \( V_G \) of 18 ms\(^{-1} \) with a wind direction \( (\theta) \) from 1\(^\circ\). The predicted \( V_I \) (Section 3.3) was \( .32 \) ms\(^{-1} \) with a polynya length of 112 km. The measured polynya orientation and length were 0\(^\circ\) and 105 km respectively.

The resultant St. Lawrence Island polynya (Figure 4), March 19, 1988, edge drift and orientation (prior five day period March 14-18, 1988) was due to an average \( V_G \) of 15.4 ms\(^{-1} \) and a \( \theta \) of 68\(^\circ\). The predicted \( V_I \) was \( .28 \) ms\(^{-1} \) and predicted edge drift was 120 km. The measured polynya orientation was 60\(^\circ\) from north, using the southwestern extreme edge. The polynya's western edge drift was 115 km.

4.2 Nunivak Island

The March 13, 1988, image (Figure 5) shows a Nunivak Island lee polynya
Figure 3. DMSP image taken March 14, 1988. The apex of the polynya south of St. Lawrence Island (L) lines up with the 170°W meridian.

Figure 4. DMSP image taken March 19, 1988. Taking the apex at the southwestern extreme edge, the triangular polynya to the lee of St. Lawrence Island (L) has an orientation of approximately 60°.

with evidence of two earlier sequential prevailing winds. The eastern edge of the polynya changes orientation at the 165° meridian. The three day period (March 10-12, 1988) had an average $V_G$ of 16.2 m s$^{-1}$ from 335°. The drift prediction (Section 3.3) from a $V_I$ of .29 m s$^{-1}$ was 76 km. The actual drift was approximately 80 km with an orientation angle of 330° at 165°W. The $V_G$ one day before March 10, 1988, was from 45° which
approximates the polynya orientation south of its intersection (eastern edge) with 165°W. Prior imagery was poor due to cloud cover.

Figure 5. DMSP image taken March 13, 1988. The lee polynya for Nunivak Island (N) changes orientation at its intersection with the 165° (bold white line) meridian from 330° to 45°.

4.3 St. Matthew Island

Figure 6 also shows an example of the St. Matthew Island polynya

Figure 6. DMSP image from March 18, 1988. The polynya associated with Nunivak Island (N) has a 65° orientation. The polynya associated with St. Matthew Island (M) has a 75° orientation. The analogy with airport windsocks is unmistakable.
simulating a windsock. The average $V_G$ for a five day period (March 13 (noon) - 18 (noon)), was 20.3 ms$^{-1}$ from 83°. The predicted $V_I$ (Section 3.3) and resultant ice drift were .37 ms$^{-1}$ and 172 km respectively. The actual drift was approximately 160 km in a 75° direction.

4.4 Three Island Summary

The polynya length predictions for all three islands were better than 90% of the measured length and the $\theta$ predictions were within 95% of the full scale when compared to measured $\theta$'s. The predicted verses actual measurements of polynya orientation and length are summarized below.

<table>
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<th>Date</th>
<th>$V_G$(ms$^{-1}$)</th>
<th>$V_I$(ms$^{-1}$)</th>
<th>Length/km</th>
<th>$\theta$(° From)</th>
</tr>
</thead>
<tbody>
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<td></td>
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<td>P</td>
<td>M</td>
<td>P</td>
<td>M</td>
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<tr>
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<td>.32</td>
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<tr>
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<td>.28</td>
<td>120</td>
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</tr>
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</tr>
<tr>
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<td>139</td>
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<td>13-18</td>
<td>20.3</td>
<td>.37</td>
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5. SUMMARY AND CONCLUSIONS

In a very short-term, preliminary study during March 1988, DMSP imagery was used to match actual sea ice drift, in polynya areas, to predicted sea ice drift. The use of mesoscale meteorological networks (instead of synoptic networks) has been proven effective in predicting lee-shore polynya sizes and orientations for three Bering Sea islands. The reduction of $V_G$ to $V_S$ and $V_S$ to $V_I$ (Section 3.3) are relatively standard techniques. The deployment of a meteorological buoy south of the maximum Bering Sea ice edge and an automated land station on St. Matthew Island has "created the geometry" for new polynya-surrounding mesonetworks in conjunction with existing land stations.

There is an apparent time lag of 24 hours between the onset of a geostrophic wind and the windsock type tracking of the polynyi. At present, imagery has been obtained only on a daily basis. The polynyi (at this time of year) receive some solar radiation, and do not appear to close. Instead, they seem to "record" the previously prevailing wind.
Data was not obtained on polynyas creation thresholds since the ice canopy is in a perpetual "unhealed" state with polynyas failing to reach equilibrium size within a typical synoptic period of 5 days (Pease, 1987).

6. ACKNOWLEDGEMENTS

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COMPUTER SIMULATIONS OF THE PROBABILITY OF ICE ISLAND MOVEMENTS IN THE ARCTIC OCEAN

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ABSTRACT

The Monte Carlo method and a dynamic model are used to simulate ice island movement and the probabilities of ice island trajectories. The simulation is run using a two-day timestep for random winds, and a three hour timestep for ice island velocity. Statistical monthly climatological fields of pressure were used to calculate the geostrophic wind field. The random surface wind is generated with monthly-varying fields of geostrophic wind as the mean value of wind. A simulated 36-meter water depth boundary around the Arctic Ocean is adopted as a boundary of ice island movement. The simulation grid scales are 300 kilometers for surface wind and 50 kilometers for ice island motion and probability calculation in each direction of an individual grid. The ice islands are randomly generated in time and space along the coast of Ellesmere Island, Canadian High Arctic. With some modification of the simulation, contours of different return periods (in years) for each square grid area (50 x 50 km) for ice islands in the Arctic Ocean have been obtained. There are two areas with a recurrence interval value of one year: the Canadian Beaufort Sea adjacent to the Canadian Arctic Archipelago, and an area north of the Chukchi Sea. Most of the remainder of the Beaufort Sea is in the area of one to ten year return periods. There is also an area of one to ten year return period near the north end of Greenland, where there is a higher frequency of ice islands escaping from the Arctic Ocean, east of Greenland.
1. INTRODUCTION

Many different shapes and sizes of ice features will interact with offshore production platforms in the Beaufort Sea and the Chukchi Sea. The most extreme ice features in the Arctic Ocean are ice islands or tabular icebergs. Because of their size and large-scale drift patterns, there is a possibility of ice island interaction with offshore structures. It then becomes necessary for the structure designers to know the recurrence frequencies of ice islands in a local area where the structures are to be established. The direct approach to determine the probability is a statistical analysis of observational data on ice island trajectories. Unfortunately, this data is very limited at the present time. An alternative approach is a computer simulation by the Monte Carlo method. The authors have used this method and an initial dynamic model to simulate ice island movement and the probability of ice island trajectories (Li Fu-cheng et al., 1988). The further development of the dynamic model and the details of treatments on driving forces, environmental conditions and computations involved in the computer simulation, are presented in this paper.

2. MODEL DOMAIN

The domain used in the simulation includes most of the Arctic Ocean and some marginal seas, except the shallow water areas, and is surrounded by simulated land boundaries and three open water boundaries (Figure 1). Ice islands will ground on the sea floor when they move towards the shore in shallow water coastal zones, and the water depth at which they will ground depends on the ice island thickness. On the basis of recent ice island thickness observations (Jeffries et al., 1988), a 36-meter water depth contour was considered to be appropriate as the land boundary, with some simplification on the broad continental shelf off Siberia. In the simulation, once the ice island reaches the boundary it stops moving towards the coast and can only move in a direction along or away from the coast. The open water boundaries are considered to be the main connections of the Arctic Ocean with other oceans, allowing ice islands to move out of the Arctic Ocean. The first one is simply represented as a straight line from the northeast end of Greenland to Severnaya Zemlya. The second one is at the shallow and narrow Bering Strait. The final open
Figure 1. Simulation domain. $56 \times 51$ grid with a resolution of 50km.
water boundary is at the Amundsen Gulf, between Banks Island and the North American mainland. Once an ice island moves beyond one of the open water boundaries, it is considered to have escaped permanently from the Arctic Ocean. There are also other connections from the Arctic Ocean through the Canadian Arctic Archipelago channels. However, these passages are usually covered by fast ice, and ice islands penetrate them only infrequently; thus, these connections are considered as land boundaries in the simulation.

The simulation is performed on a $56 \times 51$ element grid with a resolution of 50 km for ice island movement, and a $10 \times 9$ element grid with a resolution of 300 km for monthly-averaged wind field, and water current field.

3. WIND AND WATER CURRENT

The model was run with a two-day timestep of surface wind transformed from geostrophic wind. As the Arctic Ocean itself is relatively flat and uniform, a single transforming relation, $V_g = 0.6 \bar{V}_s e^{i2\pi}$ (Albright, 1980) was used. Geostrophic winds were randomly generated with monthly-varying mean values calculated from monthly-averaged pressure maps of the Arctic Ocean (Colony, 1987), representing a refinement as compared to the previous use of quarterly maps (Li Fucheng et al., 1988).

In general, the annually-averaged surface geostrophic wind field over the Arctic Ocean is an anticyclonic system. When considered over short periods of time (months), however, it is extremely variable (Figure 2). The maps from October to May show that the sea level air circulation is basically dominated by a large high pressure center over the west portion of the Arctic Ocean, i.e., anticyclones are common over the winter frozen ocean (Colony, 1987). The highest mean pressure gradient period appears in December. After May, the mean pressure field undergoes rapid change, high pressure gradients are weaker and the prevailing air streams are directed from the Chukchi Sea to the Greenland-Spitsbergen area. In summer (August), there is a relatively weak low pressure center near the North Pole, and the prevailing circulation is cyclonic. In September, the low pressure center is replaced by a prevailing weak air stream from the Siberian
Figure 2. Monthly averaged pressure maps over the Arctic Ocean (after Colony, 1987).
continent over the polar region to the Canada-Greenland area (Colony, 1987).

From an analysis of observed data, a threshold wind speed of 5.25 m/s appears to be necessary to initiate ice island motion (Lu, 1988). A 5.00 m/s threshold wind speed was used in the simulation.

The pattern of surface water current in the Arctic Ocean is generally a slow westerly drift, forming a large clockwise gyre over the major part of the Arctic Basin. The greatest volume of water leaves the Arctic Ocean through the western part of the passage between Greenland and Svalbard. The inflow to the Arctic Ocean through the Bering Strait is not insignificant, and the influence of water currents on ice island motion in the Chukchi Sea is considered in the simulation. Time invariant surface water current data for the Chukchi Sea (Johnson, 1987) were used to compute the water force. The velocity range is from 0 – 30 cm/s. The current is generally northward from the Bering Strait, and then is divided into two currents, one toward Wrangel Island, and another toward the northeast along the coastline from Point Hope to Point Barrow. Surface current data (Brower et al., 1977) near the Alaskan Beaufort Sea area were also used to compute water stress. The currents are generally westward with a velocity range of 2 cm/s to 30 cm/s. In the other areas of the Arctic Ocean, the water current influence on ice island motion was not considered and is to be studied further in the future.

4. ICE ISLAND PARAMETERS

Ice islands calve from the ice shelves located on the north coast of Ellesmere Island in the Canadian High Arctic (Jeffries et al., 1988). Once they break off an ice shelf, ice islands become embedded in the pack ice and drift around the Arctic Ocean (Sackinger and Yan, 1987). In this simulation, the ice islands are spatially-uniformly random-generated along the north coast of Ellesmere Island, and temporally over a 12 month interval.

Ice island geometries are important for computations of forces acting on it, e.g. air drag, water form drag and water surface drag. On the basis of statistical results of ice island geometries given by Jeffries et al. (1988), the ice island length is uniformly random-generated from
0.1km to 10.0km, and the ratio of width to length of an ice island is uniformly random-generated from 0.33 to 1.00. The initial thickness of an ice island is assumed to be 42.5m (Jeffries, 1988). Ice islands drifting around the Arctic Ocean experience melting on the exposed top surface, so that the thickness of ice islands gradually decreases during drift. The melt rates are related to the temperatures, drifting time, cloud cover, and ocean currents, but there is very little Arctic observational data available on this. In the simulation, the thinning rate of ice islands is assumed to be 0.5m per year based upon data from ice island T-3 and Hobson’s Choice Ice Island.

Tracking data shows that the ice island movements are far from steady state and transient processes are very common during the movement. Thus the acceleration term in the momentum equation is important, and a 3-hour timestep is used for computing the acceleration in the simulation. In the near shore area, a empirical relation between residual force and ice island velocity (Lu, 1988) is being used in the simulation. Evidence from T-3 and other ice islands indicates that ice islands can ground on the seafloor and remain stationary for long periods of time. The simulation model takes account of ice island grounding at boundaries, and refloating is assumed once the random wind component parallel-to-shore or offshore is greater than 5.0m/s, with an assumption of negligible soil resistance.

5. SIMULATION RESULTS AND DISCUSSION

The simulated results of probabilities of ice island trajectories are plotted in the form of differential return period (years) contours over the Arctic Ocean (Figure 3). The contours represent the recurrence interval (years) of ice islands in a square area of 50 x 50km. The results show that there are two zones of highest recurrence. One is near the Canadian Beaufort Sea, which is likely due to ice islands originating at Ellesmere Island and which are then driven southwestward by northeasterly winds along the Canadian coast. Another high recurrence zone is near the Chukchi Sea, which is likely due to ice islands being driven through the Alaskan Beaufort Sea by easterly winds to the boundaries of the Chukchi Sea confined by boundaries and currents from the Bering Strait, then pushed back to the Arctic Ocean under the influence of ocean currents. There is a broad area of 1 to
Figure 3. Simulated return period contours (years) of ice islands in the Arctic Ocean.
10 year recurrence interval in the central ocean, and the gradient of probability is high along the Alaskan Beaufort Sea coast and in the Chukchi Sea. The contours are deflected toward the Arctic Ocean at the Chukchi Sea due to the influences of Bering Strait water inflow. There is a high probability zone near the north end of Greenland, which implies that most of the ice islands escape out of the Arctic Ocean through the narrow passage between Greenland and Svalbard.

With the limited amount of observed data on ice island trajectories, the Monte Carlo method is a useful approach to the analysis of the probability of ice island trajectories. The Monte Carlo method and a dynamic model can be used to simulate ice island movement and the probabilities of ice island trajectories. The simulation results show that the return periods are sensitive to the wind and currents. Besides the return periods, the speed distribution of an ice island for each grid area is also important for determining impact probabilities with a structure. The combination of tidal current effects and wind-driven motions within an individual grid area of $50 \times 50 km$ will be studied in the future. In the summer, there are open channels in the Canadian Arctic which allow ice islands to move out of the Arctic Ocean, e.g. Nares Strait. Therefore, further model development is planned with consideration of more open boundaries.

6. ACKNOWLEDGEMENT

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STUDIES OF SEA ICE FORCING DURING MIZEX'87

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ABSTRACT

During the Winter Marginal Ice Zone Experiment (MIZEX'87) the atmosphere, ocean and sea ice was investigated in the ice edge zone between 77°N and 80°N in the Fram Strait. The seasonal variation of the ice edge position is small in this region, reflecting the strong influence of warm Atlantic water and topographical steering. The mean ice edge is bounded eastward by the core of the East Greenland Current, a narrow, topographically steered current which is the most important mechanism for transportation of ice from the Arctic Ocean to the Greenland Sea. Superimposed on the mean ice edge position, is a mesoscale variation confined to a 100 km wide belt. This mesoscale variation has a time scale of a few days, and is often caused by oceanic eddies with a typical horizontal scale of 30 km. Local ocean jets can create ice tongues which are advected out in open water. Divergence and convergence in association with upwelling and downwelling can open up or close leads in the ice.

Winds generated by synoptic lows or local polar lows which are often observed in this area, are also important forcing mechanisms on the ice. A strong wind event (20 m/s) can move ice floes 30 - 40 km in one day. During on-ice winds the ice edge becomes compact and well defined. Increased compactness causes greater internal ice stress, which inhibits further motion of the ice. If the wind is in opposite direction, or an ocean eddy erodes the ice edge, ice floes can be transported to areas of warm water where melting becomes dominant. The forcing from wind is proportional to the drag coefficient between ice and air which is highly variable in the marginal ice zone. Over open water this drag coefficient is about $1.0 \times 10^{-3}$ while the highest values ($5.0 \times 10^{-3}$) are found at the ice edge where the ice floes are small and rough with edges.

Another important contributor to the ice dynamics is the surface waves. The
waves tend to break up the ice into floes of the same size as half the wavelength. Since the shorter waves are attenuated faster than the longer waves as they propagate into the ice, the breakup into small floes only occurs near open water.

In conclusion, the marginal ice zone is a very dynamic region where growth and propagation of sea ice is balanced by melting and breakup due to atmospheric and oceanic forcing.

1. INTRODUCTION

The Marginal Ice Zone Experiment (MIZEX) is an international and interdisciplinary program where the main objective is to study geophysical processes and the interaction between the atmosphere, the sea ice and the ocean. The highlights of the two summer experiments, carried out in 1983 and 1984, are published in EOS (MIZEX Group 1986), Science (Johannessen et al. 1987a) and in a Journal of Geophysical Research Special Issue on Marginal Ice Zone Processes (June, 1987). Summaries from the winter experiment in 1987 (MIZEX87) are
published in OMAE (Johannessen et al. 1988) and EOS (MIZEX Group, 1989). Several sea ice investigations in the Greenland Sea have been published, for example Wadham's (1981) and Moritz (1988). The components of the MIZEX program are studies in oceanography, meteorology, remote sensing, sea ice physics, ocean acoustics, and marine biology. In the present paper, we limit ourselves to discuss some aspects of the dynamics of the sea ice during winter conditions in a region of strong mesoscale activity.

MIZEX'87 was carried out in the Fram Strait and the Barents Sea (figure 1) during a three week period in March and April 1987. The investigation platforms were two open ocean ships, one icebreaker with helicopter, several drifting buoys, three aircraft, and the NOAA satellites. An important aspect of the experiment was the real-time downlink of Synthetic Aperture Radar (SAR) images from the aircraft to the ship. A total of 14 days of SAR images, with a resolution of 15m, provided a unique data set to investigate ice motion, ice floe size, ice concentration and various ice types. In contrast to other remote sensing data such as visual images from the Landsat and NOAA satellites, the microwave data of the SAR penetrate clouds and can therefore provide good data independent of the weather. In addition to the study of the ice itself, ice as observed by remote sensing techniques is also a useful tracer which reflects the influence from upper ocean currents, surface winds and waves.

2. LARGE-SCALE OCEAN CIRCULATION AND ATMOSPHERIC FORCING

Ice forcing is a combination of oceanic and atmospheric dynamics and thermodynamics on various scales. An example of sea ice distribution in the Fram Strait and the Barents Sea is shown in figure 1 which was obtained from a NOAA satellite on March 26th. On the western side the East Greenland Current carries cold Polar Water and ice from the Arctic southwards towards Iceland. On the eastern side of the Fram Strait and in the southern Barents Sea, the ocean is ice free because of warm Atlantic water transported northwards by the North Atlantic Current. During a two week period, when northeasterly winds prevailed in the Barents Sea, ice was steadily transported out into the open ocean, but the ice edge did not change its position significantly. This shows how the transport of ice is balanced by melting due to warm water in this area. This balance is also important in the Fram Strait, where the ice edge position shows little seasonal variation compared to the Barents Sea. It is noteworthy how the ice is broken up in floes due to the action by wind and current. In the interior of the pack ice the
Figure 2. Wind speed and direction, ice drift, and north-south component of the relative current between ocean and ice from three days of April. During most of the experiment the wind was northerly, the ice drifted southwards, and the current 2-3 m below the ice bottom was northerly relative to the ice. As the wind turned southerly on April 3rd, the ice drift and relative current also turned 180°.

Floes are tens of kilometers large, but approaching open ocean the ice is gradually broken in smaller floes, primarily due to wave action.

During the Fram Strait operation several drifting buoys monitored the ice motion and the ocean currents. Meteorological data showed that moderate northerly winds (5 - 10 m/s) prevailed, and satellite tracked buoys documented that the ice near the ice edge drifted southwards at 30 - 50 cm/s during the experiment. On April 3rd, the northerly wind was interrupted by an outbreak of southerly wind exceeding 12 m/s which caused the ice drift to reverse immediately (figure 2). This wind reversal lasted only a few hours, but was strong enough to counteract the southward ice drift caused by the East Greenland Current. The response time between wind and ice is 1-2 hours (Farmer et al., 1972). During this event, the POLAR CIRCLE measured 3-6 m/s wind speed a few kilometers into the ice, while the HÅKON MOSBY measured 8-12 m/s 10 km out in open ocean. Over open water the drag coefficient $C_a$ is typical $1.0 \times 10^{-3}$, while over rough ice of high concentration it can be up to $5.0 \times 10^{-3}$ (Guest and Davidson, 1987). For a given drag coefficient $C_a$, wind speed $U$, and air density $\rho_a$, the wind stress can be expressed by the relation
$$\tau_a = \rho_a C_a U^2$$  \hspace{1cm} (1)

Hence, in spite of lower wind speed, the wind stress can be higher over rough ice compared to open water due to a higher drag coefficient. The wind stress is an important parameter in ice drift modeling, and recent results from the MIZEX investigations shows considerable variation of $C_a$ and $U$ according to ice roughness, ice concentration and stability. Unless abundant in situ data are available it is difficult to obtain good estimates of the wind stress and in turn good ice prediction results.

3. A SIMPLE MOMENTUM BALANCE

The forces determining the drift of the ice can be inserted in a momentum balance equation

$$mD_t u = -m f \hat{k} \times u + \tau_a + \tau_w + F - mgV_H$$  \hspace{1cm} (2)

where $m$ is the mass of the ice, $D_t$ is the substantial time derivative, $\hat{k}$ is a unit vector normal to the surface, $u$ is the ice velocity, $f$ is the Coriolis parameter, $\tau_a$ and $\tau_w$ are the forces due to air and water stress, $H$ is the dynamic height of the sea surface, and $F$ is the force due to the variation in internal ice stress (Hibler, 1984). The main problem in using this equation, which is illustrated in figure 3, is to have good estimates of all the acting forces. To simplify the problem, the internal ice stress and the pressure term ($mgV_H$) can be neglected. This approximation is usually referred to as free drift (Reid and Campbell, 1962) and is used by several investigators. The wind stress is already discussed, and due to lack of wind measurements geostrophic wind is commonly used. In a similar manner the water stress can be expressed as

$$\tau_w = \rho_w C_w (U_w - u)^2$$  \hspace{1cm} (3)

where $\rho_w$ is the density of water, $C_w$ is the drag coefficient, $U_w$ is the geostrophic current, and $u$ is the ice drift. The water stress has been considered to be small compared to the wind stress, at least in areas of weak currents such as the interior of the Arctic. However, in the East Greenland Current, where surface speed varies from 0.30 m/s to 1.00 m/s, the water stress is probably critical in the momentum balance. Therefore, in the southerly wind event described in section 2 where the forces from wind and water act in nearly opposite directions,
it is assumed that the north-south components of the wind and water stress balance each other. It is assumed that the north-south component of the Coriolis component is negligible. Direct measurements of wind, current and ice drift is used to find the drag coefficient between water and ice. A combination of (1) and (3) yields:

\[ C_w = C_a p_a U^2 / \rho_w u'^2 \]

where \( u' \) is the current relative to the ice measured 2-3m below the icebottom.

By inserting numerical values of \( C_a = 4.0 \times 10^{-3}, \rho_a = 1.3 \text{ kg/m}^3, \rho_w = 1027 \text{ kg/m}^3, \) \( U = 7 \text{ m/s}, \) and \( u' = 0.20 \text{ m/s}, \) \( C_w \) is estimated to be \( 6.0 \times 10^{-3}, \) which agrees with results from other investigations. However, the drag coefficient can vary over a wide range of values (2.0 - 20.0 \times 10^{-3}) because it depends on several other parameters. A number of factors such as the roughness of the undersurface, the boundary layer thickness, the velocity profile and the stratification, also have to be considered to obtain good estimates of the water stress (Morison et al., 1987).

4. MESOSCALE OCEAN FORCING

In the MIZ several oceanic processes such as eddies, jets, fronts and surface waves have important influence on the ice. During moderate wind conditions, when the wind stress is negligible compared to the water stress, the ice act as a
passive tracer reflecting the upper ocean circulation. Under such conditions SAR

Figure 4 a) SAR image from April 2nd showing an ice edge eddy. High backscatter (white) is ice, and low backscatter (black) is ocean; b) blow-up of the SAR image showing the penetration of 200m long swell northwestwards into the ice. Inserted is a 2-D wavespectrum of a subarea near the eddy center showing: i) 100m long waves propagating 250°, and ii) 200m long waves propagating 340°; c) photograph taken from the POLAR CIRCLE near the ice edge. The ice is broken in small floes due to wave action, and between the floes is slush ice created by freezing and grinding of ice floes; d) photograph taken from helicopter approximately 20 km into the pack ice. The ice is broken into larger floes (50-100m) by the swell.
Figure 5 Composite of the ice edge, located along the shelf break, from consecutive days of SAR images. The East Greenland Continental Shelf is ice covered, while the area east of 4°W is mostly ice free. Bottom depths are in meter. The dotted and hatched areas indicate the ice extent on March 31st and April 2nd respectively. In this period a narrow jet transports ice into open water, and on April 3rd an ice-edge eddy develops.

imagery has shown a number of examples where mesoscale ocean processes, not observable in the large-scale survey in figure 1, are dominant.

The presence of eddies of horizontal scale 20 - 40 km and vertical scale deeper than 1000m, is a characteristic feature of the ocean circulation in the Fram Strait. Most of them are reported to be cyclonic, and the generating mechanisms can be baroclinic and barotropic instability, topographic steering associated with conservation of potential vorticity, and wind effects along the ice edge (Johannessen et al. 1987b). These eddies can erode the ice edge by advecting warm water into the ice (figure 4a), and by transporting ice out in warm water. In both ways, the ice melting is enhanced, and quantitative estimates suggest that the ice edge can melt 1 -2 km per day.

If the effect of current is combined with wind forcing, the ice edge can move considerably in one day. This is demonstrated in figure 5 where a northeasterly wind of 5 - 10 m/s acts on the ice in the same direction as the current, resulting in a retreat of the ice edge of 50 km in two days.

Narrow upper ocean jets, shooting out from the ice edge, are also an important contributor to the erosion of the ice edge. Several such jets, which are typical 10
km wide and 50 m deep, are observed to transport ice out in open ocean. On April 1st the amount of ice trapped by the jet (figure 5) is estimated to be approximately 400 square km. The next day the ice tongue cause by the jet, is considerably reduced, so all the ice will probably melt in two days. Another office jet starts to develop at about 77°20'N. The surface speed of this jet was later measured to be 1 m/s.

In addition to the processes mentioned above there is the effect of surface waves. The short waves coming in from open ocean break up the ice in small floes (10-20m) only a few hundred meters into the pack ice, while the longer waves penetrate several kilometers before they are scattered and attenuated. The result is a floe size distribution in which the maximum floe size increases with distance into the ice. This is demonstrated in the ice photographs in figure 4c and 4d, where typical floe size is 50 - 100 m at 20 km, and 5 - 20 m at 1 km distance from the ice edge. The small floes close to open ocean are characterized by the influence of the short surface waves, while the larger floes are broken up by the swell.

The propagation, refraction and attenuation of long waves is particularly interesting to study by means of the SAR images. In figure 4b such waves are seen to propagate in a northwestern direction through the eddy with a refraction of up to 20°. These waves have a wavelength of approximately 200m and propagate 10 - 15 km into the ice before they decay. The 2-D spectrum shows two dominant wavelengths; the 200 m waves propagating north-westwards, and 100 m waves propagating southwestwards. The former are probably caused by a distant storm occurring 2-3 days earlier, while the latter are due to the northeasterly wind in the area. By breaking up the ice, the waves play an important part in the extinction of ice in the marginal ice zone.

5. CONCLUSION

In the marginal ice zone wind stress is an important driving force on the ice even at moderate wind speeds of 10-15 m/s, mainly because of high drag coefficient between atmosphere and ice. During moderate wind conditions the most important forcing of the ice is the ocean. The mean extent of the ice is determined by the large-scale current and temperature structure of the ocean. However, on scales less than 100 km upper ocean processes such as eddies, jets, fronts and surface waves dominate the ice forcing.

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RADAR OBSERVATION ON THE SORT OF SEA ICE

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ABSTRACT

Radar observation on sort of sea ice plays an important role in the development of marine remote sensing techniques. Radar observation is very useful in practice for study on the distribution of large scale and/or local pack ice in bays, the ice-edge change, the ice lane position and etc. This paper applied remote techniques and microcomputer treatment to the sorting of ice type in Liaodong Bay of the Bohai Sea (N. China Sea). Based on the radar observation of sea ice for many years and the analysis of sea ice dissemination mechanism, the factors influencing on the sorting of sea ice by using radar technique are considered, in author's opinion, as the roughness of sea surface the thickness of sea ice and the sea conditions. The in-situ experimental results show that the rate of sorting sea ice types with radar techniques has reached over 80%. Further improvement of data process techniques and development of correct sorting possibility are called for.
INTRODUCTION

In order to monitor the floating ice on the sea along the northeast coast of the Liaodong Bay of the Bohai Sea, since the winter of 1986, the Sea Ice Research Division of the Institute of Marine Environmental Protection, State Oceanic Administration, has been making tests on the classification of sea ice in the Liaodong Bay with radar at the Ice-survey Station in Bayuquan (Fig. 1).

The radar antenna is 120m above the sea level. The observing range is limited to a range of 1.5-12 nautical miles. The test is divided into three stages: the forming stage, the serious stage and the thawing stage. The test items include the floating ice types and their radar scattering characteristics in open waters.

Fig.1 Radar station at Bayuquan
We have developed a sea ice classification system and a data-processing terminal so that the survey and classification of sea ice can be digitized.

The result of the tests is satisfactory as was expected and showed that by studying and analyzing the radar scattering characteristics of varied-typed floating ice, its physical features can be inferred.

THE SEA ICE CLASSIFICATION SYSTEM

The system uses the marine radar whose major properties are as follows:
transmitting frequency: 9375 MHz(X-band);
antenna: width of the horizontal wave beam 0.8 ;
width of the vertical wave beam 25 ;
transmitting power: 50Kw;
pulse width: 0.08us, 0.2us, 1.2us.

The digital terminal of the system is an IBM-PC/XT-286 microcomputer with a high-resolution colour display, a high-quality printer and a plotter.

The floating chart of the system is shown in Figure 2. It consists of the radar system, the sea ice radar echo signal recorder, the communication system and the digit-processing terminal. Their functions are as follows:
the sea ice echo signal recorder: transforming the radar echo signals through A/D and storing them in digital forms in the recorder; the communication system: transmitting the quantitative value of the sea ice echo in the recorder to the digital terminal processor, i.e. the IBM-PC/XT-286 microcomputer; the digit-processing terminal: analyzing and processing the
sea ice echo data, extracting the statistical characteristics of the sea ice and giving out the relevant statistical parameters with which to classify the sea ice.

![Diagram of the system]

Figure 2. The floating chart of the system.

THE WORKING MODE OF THE SYSTEM AND TEST METHOD

I. The working mode of the system

The sea ice radar echo signal recorder is a program gate detection system with the single board micro-computer as the centre. It limits the transformation of the A/D to area-detection, gate detection and the whole-range detection, etc.

1. The mode of area detection

The radar antenna is fixed at a certain position and is
observed on the oscillograph A. The gate is aimed at a certain distance on the surface of the floating ice. The recorder repeatedly makes sample recording of a distinguishing unit (15m) in the distance so as to get the characteristics of the radar echo signal which fluctuates with the time.

2. The mode of gate-detection

The radar antenna is fixed at a certain position. The gate of the oscillograph A is aimed at a certain distance. The recorder makes sequenced recording in a range of 300m and the average space value of the sea ice echo within the 300m range, which is typical of big-sized floating ice in the serious stage.

II. The test method

At the test site, the rotation of the antenna is stopped and the antenna is aimed at a block of floating ice. The recorder is turned on under the control of the PPI radar displayer and oscillograph A. The amount of data collected each time is 2K bytes. After the recording, the collected data is transmitted to the IBM-PC/XT-286 computer through the communication system. The computer then processes the data automatically, extracts the feature quantity of the sea ice and finally shows the results on the screen or prints them out.

THE RESULT OF SEA ICE CLASSIFICATION AND ANALYSIS

The sea ice in the Liaodong Bay is yearly ice. Its floating ice includes: N(new ice), R(rind ice), P(pancake ice), G(grey ice), GW(grey-white ice) and W(white ice). Their surface conditions can be divided into L(level ice), R(rafted packed ice) and H(hummocky ice).
It is known after the test that the large amount of floating ice blocks are of various sizes and shapes and are very complicated. Their distribution, the roughness of the ice surface and the thickness of the ice are quite different. We use radar to observe the scattering characteristics of the sea ice, then get their scattering coefficient and study the scattering characteristics of various types of sea ice.

In order to raise the distinguishing probability, we have paid special attention to the study of the relation between the roughness of the ice surface and the ice type under the same sea condition.

New ice and pancake ice rise and fall with the wave. The wave can be taken as a target so that the wave zone can be distinguished from the ice zone. Our system has successfully differentiated the ice zone from the wave.

In the experiments made during the winter of 1987 and the spring of 1988, we observed 232 types of floating ice, selected 45 of them as standard samples and classified them, then used the computer to make the classification.

In this article, the time and fluctuating graph (Fig. 3-10) of the scattering characteristics of several types of floating ice are given. In the graph, the abscissa is the number of samples, the ordinate is the echo voltage. We sectioned and drew out the three-dimensional fluctuating graph of time of each section so as to facilitate reading. These graphs vividly link the ice type with its roughness and given out good visual reading result. As we know, generally speaking, the scattering coefficient increases as the ice surface becomes rougher.

New ice and rind ice (Fig. 3, 4 and 5) have thin layers,
Fig. 3. Graph of the scattering coefficient of new ice with time.

Fig. 4. Graph of the scattering coefficient of R with time.

Fig. 5. Graph of the scattering coefficient of Rl with time.
Fig. 6. Graph of the scattering coefficient of P with time.

Fig. 7. Graph of the scattering coefficient of G1 with time.

Fig. 8. Graph of the scattering coefficient of G2 with time.
especially the rind ice whose surface is smooth. New ice assumes the form of tallowy ice crystal and undulates with the wave. Its time wave form is similar to the echo of the sea waves, but lack the downy details which are characteristic of the sea wave echo. The edge of the pancake ice rolls up, and is rougher than the former two. Its echo fluctuation increases evidently. Grey ice and grey-white ice and white ice are still rougher in general, and so are their echos. Interestingly, the smoothness and piling property of the same ice type can be seen clearly at a glance in the graph.
On the basis of the directly observable data shown above, we made further classification experiments with the computer and got the good result as was expected. To get rid of the influence of the distance and the different working condition of the radar, the classification is made when the original data has been converted into the scattering coefficient.

In the classification calculation, eight ice types and sea waves, altogether nine targets of forty-five samples and six floating ice categories are classified: sea waves, N, R, Ri, P, Gra, Gwh, Wh. The following is the result.

Table 1 represents the scattering coefficient of the floating ice type. As the converted form of the original data, among the forty-five samples, there is one error in the sea wave, one in P, one in Gra, one in Gwh and one in Wh. The rate of correct classification of those kinds of targets is 88.9%.

CONCLUSION

1. It is effective to take the scattering coefficient of the floating ice as the original data form and analyze the features of various type ice on this basis and then classify the sea ice.

2. The test confirms that the software for controlling and displaying images, the design for the computer, the sea ice echo signal recorder, the communication interface is reliable. In the final classifying calculation, the classification rate of the sea ice with radar is over 80%.

3. The test shows that in the study of ice classification the roughness and thickness of the ice and the sea condition are the major factors which influence the sea ice's radar
wave scattering.

Table 1. Classification for each observation.

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## Discriminant Matrix

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NUMERICAL SIMULATION OF ICE FORMATION IN FREQUENTLY TRANSITED NAVIGATION CHANNELS

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ABSTRACT

Frequent cycles of icebreaking and ice regrowth accompany frequent vessel transits of ice-covered navigation channels, usually causing a greater volume of ice to be produced in them than would have grown without transiting. Consequently, a concern for wintertime navigation is the prospect that frequent transiting may increase volumes of ice, possibly to the point that channels become impassably clogged. A numerical simulation model is developed and exercised as a means of predicting volumes of ice formed in navigation channels, of assessing whether they would become unnavigable, and of identifying optimal transit schedules which would reduce volumes of ice produced. It is shown, however, that difficulties in predicting patterns of broken and brash ice accumulation may diminish the efficacy of numerical simulation for predicting volumes of ice produced in navigation channels.

1. INTRODUCTION

Frequent vessel transits may cause navigation channels to accumulate broken and brash ice, as illustrated in Fig. 1. A potentially useful means of evaluating volumes of ice produced, is numerical simulation. At least five prior formulations have been proposed (e.g., Sandkvist 1986, Ashton, 1974). Each is based on Stefan's semi-empirical equation for ice-sheet thickening,

$$\eta_t = \alpha (\Sigma S_d)^{0.5}$$  \hspace{1cm} (1)

in which $\alpha$ = a growth coefficient (sometimes called air freezing index), $\Sigma S_d$ = accumulated freezing degree days. Space herein precludes a detailed review of the prior formulations. Suffice to note that each formulation invokes the assumption that ice covers regrow successfully over a layer of broken ice which is uniformly distributed in vessel tracks. In accordance with this assumption, each formulation yields only an average, or an equivalent, thickness of ice accumulation in vessel tracks.
and does not take into account the influences on ice regrowth of brash-ice movement and redistribution during vessel transits.

The model presented here attempts to account for the effects of brash ice redistribution during vessel transits on ice regrowth and ice formation. Formulation of the model was guided by the results of laboratory experiments conducted with an ice tank and scale-model hulls, as well as by descriptions of ice formation observed in actual navigation channels (notably by Sandkvist 1986; Kannan 1983). The results of the laboratory experiments are reported by Ettema and Huang (1988, 1989); the latter reference documents the entire study.

2. FORMULATION OF SIMULATION MODEL

The model is intended to simulate cycles of ice regrowth and brash-ice accumulation in a frequently transited channel such as illustrated sequentially in Fig. 1. A basic assumption is that vessels displace brash ice sideways and downwards, but do not move significant amounts of it along channels. Additionally, it is assumed that no ice fragments break from the ice sheet bordering the track. In concordance with these assumptions, ice formation can be briefly described as follows:

The first few transits leave an open layer of broken ice spread over the track, with some ice being cast beneath the adjoining ice sheet (Fig. 1a,b). During subsequent transits and periods of ice regrowth, more ice is broken causing the track to become increasingly covered by a thickening layer of brash ice with ridges forming beneath the ice sheet (Fig. 1c). Once the track is completely covered with a layer of brash ice, further transits cause the layer to thicken more-or-less uniformly, but lagging thickening of ridges (Fig. 1d). Also, each transit causes the entire brash-ice layer to be disrupted such that regrowth commences again. However, some brief period is required for water in the track to calm sufficiently before regrowth commences. A further factor to be considered for relatively shallow channels is that the ridges may extend to the bed and confine brash to the track (Fig. 1e).

Consider a section of vessel track filled with brash ice, as shown in Fig. 2. Conservation of thermal energy flux between ice, water and air enables the volume of ice in the track per unit area of track surface at any instant to be expressed as

\[ n_i = n_{i-1} + \beta_i a [\Delta T(P_t - t_p)]^{0.5} \cdot (1 - \beta_i) \cdot \frac{2}{b_i - 1} + \alpha^2 \Delta T \cdot (P_t - t_p)^{0.5} \cdot (1 - \beta_i) \cdot n_{i-1} \]

\[ \text{(i)} \quad \text{(ii)} \quad \text{(iii)} \]

in which term (i) = value of \( n_i \) immediately prior to the \( i \)th vessel transit; term (ii) = average thickness of ice regrowth over open water; and, term (iii) = equivalent thickness of ice grown through, and under, accumulated brash ice occupying the track at areal concentration \( (1 - \beta_i) \). In terms (ii) and (iii), the conventional cumulative degree-days of freezing \( \Sigma D \) is modified to allow for the time required for water in the track to become sufficiently calm after vessel transit such that ice regrowth can begin. In accordance with this condition, \( \Sigma D \) is modified to \( \Delta T(P_t - t_p) \); with \( \Delta T = 0^\circ\text{C} \cdot T_a \), \( P_t = 1/t_t = \text{period between transits, and } t_p = \text{period for calming of water before regrowth begins.} \) If \( P_t < t_p \), there is insufficient time for ice regrowth, as is the case for convoying. At comparatively high frequencies of
Figure 1. Ice formation in a frequently transited navigation channel (no conveyance of ice along track).
transiting, when \( p_t \cdot t_P \) approaches zero, little opportunity occurs for ice regrowth, and the effect of transiting is to maintain an open track.

During each transit of a track when fully covered with brash ice, regrown ice is broken, mixed with existing brash ice and bulked to form a layer of uniform thickness

\[
\eta_{bi} = \frac{(1 - \varepsilon_i) (1 - \eta_{bi-1}(1 - \eta_i))(1 - \phi_i) + (\eta_i \cdot \eta_{i-1})}{(1 - p)},
\]

in which \( \varepsilon_i \) = proportion of brash, or broken, ice displacement from the track to the ridges. It is assumed that, between transits, ice growth through and beneath a layer of brash layer of thickness, \( \eta_{bi} \), and porosity, \( p \), can be reasonably represented as growth of an equivalent monolithic ice cover of thickness \((1 - p)\eta_{bi}\).

Thus far no account has been made of brash ice displaced to the ridges. A simple mass-conservation relationship can be formulated to take into account brash ice accumulation both within the track and in the ridges. The volume of ice displaced per unit length of track, and supplied to each ridge, is \( 0.5 \eta_{bi} B (1 - \varepsilon_i) \). Each ridge is assumed to thicken and broaden as a heaped pile. If at any instant ridge thickness is \( \eta_{ri} \) and its shape is defined in terms of an angle of static (brash ice) repose, \( \theta_r \), ridge volume is

\[
V_{ri} = \eta_{ri-1}^2 \tan \theta_r + \frac{\varepsilon_i B \eta_{bi}}{2(1 - \varepsilon_i)} + \frac{(1 - p)^2 \eta_{ri-1}^2 + \frac{\alpha^2}{p} \Delta T (p_t \cdot t_P)^{0.5} - (1 - p)\eta_i \cdot 1}{2} \eta_{ri-1}^2 \tag{4}
\]

in which term (i) = volume of ice, per unit length of track, already included in the ridge before the \( i \)th transit; term (ii) = volume of ice, per unit length of track, displaced from the track; and term (iii) = volume of ice grown at each ridge, per unit length of track between the \( i-1 \) and \( i \)th transits. Term (iii) is small compared to terms (i) and (ii), and can be neglected. Ridge thickness, \( \eta_{ri} \), and width, \( W_i \), after the \( i \)th transit can be expressed respectively as

\[
\eta_{ri} = \left( \frac{V_{ri}}{\tan \theta_r} \right)^{0.5} \tag{5}
\]

\[
W_i = 2 \eta_{ri} \tan \theta_r \tag{6}
\]

Maximum values of \( \eta_{ri} \) and \( \eta_{bi} \) are, of course, limited to channel depth and water currents which may entrain brash ice.

A major impediment to developing a numerical model for predictive or operational purposes is that several quantities are difficult to know beforehand. The quantities include \( \beta, p, \varepsilon, \theta_r \), and \( t_P \). Their values are influenced by vessel hull shape, draft, propeller configuration and speed, channel depth, width and currents, frequency and total number of transits, and size of broken or brash ice. For the study described herein, values of \( \beta, p, \varepsilon, \theta_r \) and \( t_P \) were obtained from laboratory experiments with a wedge-shaped hull. A generic numerical model for simulating and predicting ice formation would require accurate relationships between the quantities in terms of the above-noted influences.

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Figure 2. Modeled geometry of brash-ice accumulation across a vessel track.

Figure 3. General transit schedule.
3. TRANSIT FREQUENCIES

Vessels may transit channels at a single frequency, at combinations of frequencies, or at random frequencies. Typically, though, transits conform to some loose schedule; the simplest ones being daily transits limited to daylight hours. A general schedule, shown in Fig. 3, is as follows. After an initial period of ice-cover formation, \( P_1 \), a sequence ensues of \( n \) transits at time intervals \( P_1 \), for a total duration \( P_S \). Sequences of transit frequencies can be intermittent, being separated a period of no navigation, \( P_O \). A fairly simple schedule that can be defined in terms of three periods, \( P_1, P_S \) and \( P_O \), gives rise to three transit frequencies:

(i) \( f_1 = 1/P_1 \), defines the frequency of transits within a sequence of transits (e.g., one every two hours);
(ii) \( f_S = n/(P_S+P_O) = n/P_n \), defines the frequency of transits within a navigation period (e.g., six transits every day), and,
(iii) \( f_n = 1/P_n = f_S/n \), defines the frequency of sequences within a navigation period (e.g., one sequence of transits daily).

4. EXERCISING THE NUMERICAL MODEL

The numerical model was exercised with the aim of determining the effects of transit frequency(ies) on ice formation, and to ascertain if, in fact, scheduling of vessel transits is a feasible means for reducing ice regrowth.

Ice formation is simulated for a representative channel that is transited in frigid air for a navigation period of thirty days; a suitably long period over which the computations would illuminate the main features of ice formation. It is assumed, somewhat conservatively, that no snow falls in this period. The channel is initially taken to be deep and wide so as to exclude the influences of channel geometry. All computations are based on \( \alpha = 24\text{mm/(°C-day)}^{0.5} \), a value suggested (e.g., by Ashton 1974) for ice growth on several inland waterways in the U.S. Values for \( \beta \) and \( \varepsilon \) were evaluated from Figs 4 and 5 which were obtained from the laboratory experiments described by Ettema and Huang (1988,1989), from which \( P = 0.5 \) and \( \theta_r = 30^\circ \) are taken also; the reader is referred to the latter reference for background to Figs. 4 and 5. As the wake behind each transiting vessel exposed openwater, minimum \( \beta \) is taken as 0.1. As it is evident from Eqs (1) and (2) that the volume of ice grown increases with decreasing air temperature and increasing \( \alpha \), values of \( \eta_i, \eta_B \) and \( \eta_f \) are hereafter normalized with \( \eta_S = \) thickness of virgin ice sheet over the navigation channel (computed using Eq. (1)).

4.1 Influence of Transit Frequency

The relationship between \( \eta_i/\eta_S \) and \( f_i \), after thirty days of transiting under air temperatures of -5, -10 and -20°C, shows that \( \eta_i/\eta_S \) increases with increasing \( f_i \), until attaining a maximum value, (Fig.6). Values of \( \eta_i/\eta_S \) form essentially a single curve for the three values of \( T_a \) used in the computations. The slight variations with \( T_a \) are attributable to slight variations in values of \( \beta \) selected from Fig.4 That
Figure 4. Variation of $\beta$ with $a(n\Delta T/\eta)^{0.5}/D$ and $f_t$.

Figure 5. Variation of $c$ with $(D^l - \eta_l)/\eta_r$; with $D^l$ = ice displacement depth.

Figure 6. Variation of $\eta_l/\eta_s$ with $f_t$. 

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a maximum value should occur with \( I_1 \) is evident from inspection of Eq. (2). Ice volume, or \( \eta I / \eta S \), increases with \( I_1 \), especially when \( 1/I_1 \) (or \( P_1 \)) >> \( I_P \). However, when \( 1/I_1 \) approaches \( I_P \), the time available for regrowth diminishes until there is insufficient time for regrowth to occur. Herein, as \( I_P \) is taken to be 0.25 hours, no regrowth occurs when \( I_1 = 96 \) transists/day. This frequency is well above the frequencies at which most navigation channels are likely to be transited, although it is possible that some heavily trafficked harbor channels and dock areas may be transited at such an intense frequency. In practical terms, however, increased frequency of transiting increases volume of ice produced in most navigation channels.

Though the numerical model involved values of \( \beta \), and \( p \) and \( \theta_0 \) taken from the ice tank experiments, it is useful to compare measured values of \( \eta I / \eta S \) with the predicted trend, as shown in Fig. 6.

It is evident in Fig. 7a-c that, though the volume of ice produced during frequent transiting increases both with increasing duration of navigation period (expressed simply as \( \sum d = (10^\circ C) \times \) (time) and increasing \( I_1 \), values of \( \eta I / \eta S \), \( \eta B / \eta S \), and \( \eta P / \eta S \) follow somewhat complex trends. For each value of \( I_1 \), \( \eta I / \eta S \) increases comparatively rapidly during initial transits at large \( I_1 \), because initially larger values of \( \beta \) are associated with larger values of \( I_1 \). Once \( \beta \) values have decreased to constant values and the track is essentially fully covered with a layer of brash ice (though \( \beta = 0 \)), values of \( \eta I / \eta S \) increase at diminished rate with time or \( n \). Larger values of \( I_1 \) produce greater rates of increase of \( \eta I / \eta S \). The variation of \( \eta B / \eta S \) with duration of navigation \( P_T \) (Fig. 7b) is similar to that between \( \eta I / \eta S \) and time or \( n \). Values of \( \eta P / \eta S \) (Fig. 7c) almost initially attain their maximum value, then gradually diminish.

4.2 Merits of Scheduling Transits to Reduce Ice Growth

Scheduling of vessel transits is a seemingly attractive, though heretofore an unproven, means to reduce ice production in frequently transited navigation channels. In order to ascertain whether a given number of transits could be scheduled to reduced ice regrowth, the numerical model was exercised to determine values of \( \eta I / \eta S \), \( \eta B / \eta S \), and \( \eta P / \eta S \) associated with transits variously scheduled within a 30-day navigation period (\( P_T \)), with \( T_a = -10^\circ C \) and \( \alpha = 24 \) mm/(°C-day)\( \cdot 0.5 \). In accordance with Fig. 3, scheduling entails varying \( I_1 \) and \( I_S \). In the present exercise, three values of \( I_S \) are used: \( I_S = 2, 4 \) and 6 transists/day. The period between transits, \( P_1 \) or \( 1/I_1 \), is varied from 0.5 to 12 hours. For example, a schedule may comprise a transit sequence of 6 transists/day (\( I_S \)), with individual transits at hourly intervals (\( P_1 \)) and a period between a transit sequence of \( [24 - (6 - 1)] = 19 \) hours.

Given a prescribed number of daily transits, or \( I_S \), values of \( \eta I / \eta S \), \( \eta B / \eta S \), and \( \eta P / \eta S \) are only mildly affected by variation of \( P_1 \), as shown in Fig. 8a-c. Generally, less volume of ice growth results with smaller \( P_1 \) for constant \( I_S \), and more ice growth results with larger \( I_S \) and constant \( P_1 \). The smaller values of \( P_1 \) approach \( I_P \) such that the net period for ice regrowth is diminished. Fig. 8b, for example, shows that a daily sequence of 4 transits (\( I_S = 4/day \), 0.5 hour apart (\( P_1 = 0.5 \) hours) produces about 18 percent less ice growth than does a sequence 6 hours apart (\( P_1 = 6 \) hours); the commensurate

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reduction in layer thickness between the two schedules is about 11 percent. For an ice cover thickness of about 420 mm, the additional thickness of ice growth over the track during 30 days is less than about 75 mm. The practical implication of the results shown in Fig 8a-c is that there is no significant advantage in scheduling transits for the purpose of reducing the volume of ice regrowth.

5. CONCLUDING REMARKS

Values of $\eta_s/\eta_S$, $\eta_b/\eta_S$, and $\eta_f/\eta_S$, or predictions of ice formation generally, are influenced by values assumed for $\beta$, $\epsilon$, $\rho$, and $\theta_f$. These terms describe brash ice accumulation in a track, and extent of openwater exposed for ice regrowth. The present computations are based on values for $\beta$, $\epsilon$, $\rho$, and $\theta_f$ obtained from ice tank experiments performed under fairly ideal conditions (wide and deep channel) and with a simplified hull shape (Ettema and Huang 1988). Different values for $\beta$, $\epsilon$, and $\rho$ may prevail for other hull shapes and channel conditions. It is likely that diverse hull shapes, varying hull speed, as well as unsteady weather conditions, would cause $\beta$, $\epsilon$, and $\rho$ to vary rather unpredictably. Therefore, it is doubtful if a numerical model can be used with sufficient reliability so as to be used as an operational tool for predicting volumes of ice produced in frequently transited channels.

6. REFERENCES


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7. ACKNOWLEDGEMENTS

This study was funded, under Contract No. DACA89-85-K-0018 by the U.S. Army Corps of Engineers Cold Regions Research and Engineering Laboratory (CRREL). The assistance of H.P. Huang in performing the study is gratefully acknowledged, as are useful discussions with CRREL personnel.
Figure 7. Variation of (a) $\eta_l/\eta_s$, (b) $\eta_b/\eta_s$, and (c) $\eta_p/\eta_s$ with $\Sigma S_d$ for varying $f_t$. 
Figure 8. Variation of $\eta_t/\eta_s$ and $\eta_b/\eta_s$ with $P_t$ for (a) $f_s = 2$/day,
(b) $f_s = 4$/day and (c) $f_s = 6$/day.
ICE MANAGEMENT IN THE BARENTS SEA

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ABSTRACT

Exploration drilling is moving further north in the Barents Sea. In 1988 the rig "Ross Rig" drilled two wells north of 73° latitude southeast of Bjørnøya. In order to maintain a drilling operation with a minimum of downtime as well as risk due to ice incursion, it is necessary to develop a strategy for effective forecasting and response to the ice threat.

This paper briefly describes the ice conditions affecting marine structures/operations in the western part of the Barents Sea. The ice regimes are compared with those in Canadian waters where exploration drilling has been carried out for more than a decade. As a part of the ESSO/SINTEF Arctic Research Program (ESARC), the performance of state of art ice management techniques was estimated, primarily from Canadian operations. The adoption and applicability of these management techniques to the Barents Sea are presented.

1. INTRODUCTION

The ESARC program covers a range of activities related to exploration drilling and to all-year oil production in the Barents Sea. The program has conducted a site specific feasibility study of exploration, production and transportation alternatives. Three example development sites in the Barents Sea were chosen to study operating conditions in the seasonal ice zone.

The performance of different ice management techniques has been estimated for the environmental conditions at the northernmost of these example sites in the Barents Sea. The drilling is assumed to be performed
by using standard floating drilling units, either semi-submersible drilling rigs or drillships.

The topicality of ice management techniques for the Barents Sea was stressed in 1988 when the semi-submersible drilling rig "Ross Rig" was operating north of 73° latitude. The activity was terminated late November 1988. By that time ice features had been observed only 6 nautical miles from the rig (Vefanmo et al., 1988). This was the first time ice management was employed within Norwegian jurisdiction.

2. THE WESTERN BARENTS SEA ICE REGIME

Investigations in the Barents Sea have revealed great interannual variations in the dynamics, extension and compositions of the ice fields. By far the most common ice type in the Barents Sea is the locally formed first-year ice mixed with second-year ice formed in the same area. Periodically multi-year ice is imported from the North. Icebergs are also present in the Barents Sea.

Sea ice

The ocean polar front has a strong controlling effect on the ice edge during winter and early spring in the Barents Sea. If the wind causes ice to drift across the front into warmer Atlantic water to the South, the ice melts rapidly. The western flank of the front is remarkably stable with an annual variation within a range of about 100 km (see Figure 1 where the maximum ice extent is indicated).

Ice charts from the Norwegian Meteorological Institute (DNMI) for the period January 1976 to July 1988 have been visually inspected to estimate occurrence and duration of ice periods in the area of interest (Jensen et al., 1988). These estimates are presented in Figure 2 where a solid line indicates presence of ice.

Figure 2 shows a window of about 3.5 months between July and November when no ice has been observed in our study area for the last 12 years. The weekly ice charts show that the ice edge can change position very rapidly. This is caused either by freeze-up or drift of the pack, the latter being of most concern with respect to ice management.

Surveys in the area have revealed that the marginal ice zone normally consists of brash ice and small floes of thickness 20-100 cm with floe sizes within the range 5 - 20 m across, even smaller towards the ice edge (Jensen, 1988; Korsnes, 1988). A maximum first-year ice thickness of 173 cm was recorded at Hopen in spring 1969. Unless the ice is packed by southerly winds the ice edge consists of bands of ice often several kilo-
metres long. In January 1988 a large number of thicker ice features like bergy bits, growlers, old ridges and 20-60 m floes more than 4 m thick were observed (Jensen, 1988).

Figure 1. Maximum ice extent for 1/10 concentration or higher in the Barents Sea 1979-1985. After Midthun and Loeng (1987).

Figure 2. Ice incursion at the study site during the period January 1976 to June 1988 (Jensen et al., 1988). The solid lines indicate presence of ice.
Icebergs

Icebergs in the Barents Sea originate from glaciers on Noroastlandet, Spitsbergen, Edgeøya and Kvitøya. In addition pieces of ice islands advected from the Polar Ocean and icebergs from glaciers at Franz Josef Land and Novaja Zemlja are present.

The annual number of icebergs fed into the Barents Sea is not known, but it is generally accepted that the glaciers are surging (Liestøl, 1969) resulting in a highly variable production of icebergs.

Carstens et al. (1989) have made a "first raw guesstimate" of iceberg production based on comparison with measurements from Greenland, suggesting these volumes in terms of water equivalent:

- Svalbard 1.5 km$^3$ per year
- USSR 3.0 km$^3$ per year

We believe that only half of the USSR production goes directly into the Barents Sea.

The lack of statistical information makes it difficult to draw any conclusions about the flux of icebergs through the region. However, from recent observations (Løset et al., 1989), we know that a considerable number of icebergs can be grounded along the slope of Spitsbergenbanken even towards the end of June.

Figure 3 shows the satellite tracking of an iceberg drifting south of latitude N74°  late April 1988. The satellite buoy was deployed by entering the iceberg via helicopter on 20 March 1988 as a part of the IDAP Vessel Deployment Project. The iceberg was photographed by a Royal Norwegian Air-Force aircraft on 5 May 1988. The iceberg is depicted in Figure 4 which clearly shows how the iceberg has been weathered by the waves after deployment of the Argos transmitter.

When the semi-submersible drilling rig "Ross Rig" was operating southeast of Bjørnøya, NHL performed daily ice forecasting. During this forecasting period the needs for models predicting iceberg drift and deterioration were highlighted. Wednesday 23 November 1988 the supply vessel "Finn Barents" encountered a nearly deteriorated "dry dock" type iceberg in position N73° 23', E21° 45' (Vefsnmo et al., 1988). The horizontal dimensions were estimated to be 5 by 10 metres with two peaks respectively 3 and 5 metres high and a total mass of approximately 500 tonnes.
Figure 3. Iceberg tracked by satellite. The positions are labelled with day numbers (Day/GMT).

Figure 4. Weathering of the iceberg with trajectories plotted in Figure 3.
3. COMPARISON TO GRAND BANKS ENVIRONMENTAL CONDITIONS

A comparison of different areas where ice management is performed shows that the environmental conditions at our study site in the Barents Sea in many ways are similar to what we find on the Grand Banks:

- The ice regime in both areas includes both icebergs and sea ice.
- Both areas are relatively close to the maximum ice extent. Ice incursion is probably more common at our study site.
- The distance to shore base is about 450 - 500 km.
- The water depths are comparable, around 100 metres.

One important difference is that the Bjørnøya area is north of 74° latitude while the Grand Banks are around 48°. This difference in latitude will have a major impact on the ice management system during late autumn and winter drilling since visual spotting and surveillance will be of very limited value due to darkness.

From winter observations of icebergs in the Barents Sea it appears that the icebergs here are more tabular than on the Grand Banks, hence they should be easier to tow since the risk of slippage is reduced. During summer conditions, however, when the icebergs are drifting in open waters, their shape will be more rounded due to deterioration by wave action (Figure 4).

Hotzel and Miller (1985) show that about 70% of the icebergs occurring at the Grand Banks are less than 250,000 tonnes. Volume estimates of about 200 icebergs photographed in the Barents Sea late March 1988 indicate that only some 45% of these icebergs are less than 250,000 tonnes (Næss and Levås, 1988). It should be born in mind that the statistical estimates are based on a limited number of icebergs with a poor temporal and spatial resolution. Still there is no evidence that the icebergs in the Barents Sea are significantly smaller than on the Grand Banks.

4. ICE MANAGEMENT TECHNIQUES FOR THE BARENTS SEA

With environmental conditions appearing to be close to what is found on the East Coast of Canada, we assume that the key elements of ice management for the Barents Sea will be similar to the Grand Banks activity, in some cases modified.

Norway has no governmental agency providing extensive regional ice information as a support for operations in ice-infested waters. The information is restricted to publication of weekly ice charts mainly based on satellite images.

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An operator will have to provide all necessary ice surveillance for operations in the Barents Sea. During the period from late March to early October, visual reconnaissance from an aircraft may be sufficient. Also in the Barents Sea the marine radars and visual observations will be most important within the alert zones (see Figure 5). For tactical surveillance the search radar operated from a fixed wing aircraft is probably the single most effective sensor for the selected study site. With the general drift direction of ice and icebergs towards the south-west, regional surveillance by SAR is probably a very useful supplement. One important difference from the Grand Banks is the darkness during autumn and winter time.

When establishing contingency plans for ice management, a series of alert zones are typically established around a drilling unit. In principle these plans are similar in that the alert zones are defined by concentric circles with the drilling unit in the centre. The radius of each circle is a function of the shut down time for the activity on the drilling unit and the minimum estimated travel time for the ice feature to impact the unit. The size of the alert zones are changing according to on-going operations as well as ice situation. Hotzel and Miller (1985) have shown the following tactical alert zones used by Petro Canada on the Grand Banks:

![Alert Zones Diagram](image)

(1) Use distance travelled in 1 hour drift time or 1 n.m., whichever is greater.

Figure 5. Alert zones (Hotzel and Miller, 1985).

Tracking zone: This is the outer zone which normally extends to the full range of detection. Ice targets in this zone are monitored and potentially threatening icebergs will be deflected where possible.
Suspend zone: This is the middle zone with a radius defined as the product of the iceberg drift speed and the time required to suspend operations (known as the T-time). If an iceberg enters this zone, operations to reduce the suspend time must be started.

Disconnect zone: The inner zone is the disconnect zone with a radius defined as the greater of one hour drift of an iceberg and one nautical mile. Once an iceberg enters this zone the drilling unit must be ready to move off location on a very short notice.

Drilling units

Two types of drilling units are considered in the ESARC ice management study:

- A winterized but otherwise conventional semi-submersible rig. Such a rig has to move off location in case of ice incursion.
- A dynamically positioned and ice strengthened drillship.

The semi-submersible rig will typically have an 8 anchors spread mooring system. The disconnect time is approximately 36 hours:

- 6 hours to secure the well and disconnect the lower marine riser unit (LMR)
- 30 hours to pull anchors (assuming 2 assisting vessels)

The disconnect time for the drillship is estimated to be 6 hours. Depending on the type of work in progress, the time to secure the well and to disconnect the lower marine riser can be considerably shorter than 6 hours.

The radius of the alert zone where ice management should be started is estimated to correspond to 48 and 18 hours of ice drift for the rig and the drillship respectively.

For purposes of this paper, we assume that the drillship can operate in up to 5/10 ice cover for first-year ice (thickness less than 100 cm) and in 10/10 cover of young ice (less than 30 cm thick), broken up by assisting vessels. It is further assumed that the drillship would be able to weather-vane to accommodate changes in ice drift directions and ice drift speed. Additional work would be required to validate these assumptions.

Modern drilling rigs like "Ross Rig" can be upgraded to operate on full dynamic positioning (DP). In that case, the disconnect time for a semi-submersible rig and a drillship will be comparable.
Deflection of ice

The response to ice includes contingency procedures and physical action to avoid contact or reduce impact forces between the drilling unit and sea ice or icebergs. Numerous devices and methods of action against icebergs as well as sea ice have been suggested. The response to icebergs in the Barents Sea may include application of techniques/devices like regular tow line, tow line with Buckley cleat, towing net, sinking/ floating tow line, ice jigger, two vessels and net, propeller washing, dual towing and washing, water cannon and splitting of icebergs with explosives. The method or device to be applied depend highly on the characteristic of the ice feature.

The most obvious way to reduce impact forces from level ice is to break up the ice unless the drilling unit move off location. Experience from icebreaker operation to reduce impact forces from sea ice is gained e.g. from the disc-shaped drilling structure "Kulluk" (Hnatiuk and Wright, 1987). Other methods include application of explosives, electro-hydraulic shock waves (Wesley and Stowell, 1985), propeller washing and water cannon.

Contingency planning

We expect the ice management at the study site in the Barents Sea to include:

1. Regional ice reconnaissance. The general drift direction of ice is from the north-east. The ship activity is very low in the area. Hence the information must either come from remote sensing by satellites, aircraft surveillance, tracking of icebergs by Argos transmitters or radar transponders, or from ship radar. Visual reconnaissance within a large area is expected to be a highly used means of regional surveillance. The frequency of regional ice reconnaissance operation will depend on the general ice conditions in the vicinity of the drilling unit.

2. Forecasting of ice drift. Drift models tuned to the area with input from surveillance, weather forecasting and statistical data will be important (Carstens et al., 1989).

3. Monitoring. Within an area around the drilling unit, especially inside the alert zones, the ice should be closely monitored from ships as well as with radars from the drilling unit, probably supported by reconnaissance from air.
4. Avoidance. Deflection of icebergs is performed by towing, water cannoning or propeller washing according to size and shape. In case semi-submersible drilling rigs are used, the rig is moved off location in case of sea ice incursion. If drillships are employed the ice can be broken up by assisting vessels.

4. CONCLUDING REMARKS

The response to ice includes contingency procedures and physical action to avoid or reduce impact forces from sea ice or icebergs. The study provides the following recommendations:

- Regular towing and use of water cannon are the two most promising methods for iceberg management in the Barents Sea.

- Icebreaking combined with propeller washing or use of water cannons for deflection of small ice features seem to be the most promising methods for management of drifting ice floes.

- Traditional icebreaking is the only recommended method for breaking up the ice cover after a freeze-up.

- Due to the high latitude, darkness will be a severe constraint to ice management operations in the Barents Sea since visual reconnaissance will be of very limited value during late autumn and winter.

The environmental conditions at our study site in the Barents Sea and the Grand Banks have several similarities: the ice regimes include both icebergs and sea ice, the areas are close to the maximum ice extent, the distance to shore bases and the water depths are comparable. In this case we foresee an adoption of the ice management techniques from the Canadian waters (Grand Banks) to the Barents Sea.

5. ACKNOWLEDGEMENT

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6. REFERENCES


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RESULTS OF LONG-TERM ICE LOAD MEASUREMENTS ONBOARD
M/S KEMIRA DURING THE WINTERS 1985-1988

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ABSTRACT

Long-term ice load measurements onboard M/S Kemira have been conducted since the winter 1985. The present paper describes the measuring system and gives a summary of the main results during the winters 1985 to 1988. The characters of the winters 1985 to 1988 are compared to the long-term averages. Long-term extreme values are evaluated for various parts of the ship based on measured 12 hour period maximum values for the different winters. The effect of winter hardness on the long-term extreme values is briefly discussed.

1. INTRODUCTION

The shell structures for merchant ships navigating in Baltic ice conditions are designed according to current ice rules, the latest of which are published in 1985 /2/. The ice-strengthening principles are based on more than 100 years experience of winter navigation in the Baltic Sea. Damage statistics from ships during the 1960's /4/ form the basis of the design load level given in the rules.

The results of full-scale ice pressure measurements onboard the polar tanker Igim /5/ and the icebreaker Sisu /6,12/ together with the theoretical work carried out by Varsta /11/ enabled a new formulation of the design ice pressure for the present rules. The main revision to the earlier rules was the considerable increase of design pressure and decrease of design load height. The basic level of design ice loads was kept at about the same level.

The ice rules include a number of empiric coefficients, which take account of the effect of ship's displacement, shaft power and ice class on the design ice loads on the bow, mid and aft shell structures of a ship. To gain more
insight into these coefficients a joint research project between Helsinki University of Technology and Technical Research Centre of Finland was started in the winter 1985, when the chemical tanker Kemira was instrumented to measure ice induced loads on various parts of the ship. This is the first attempt to measure long-term ice loads onboard a cargo ship navigating regularly to the northern Baltic. In this paper a summary of the main results during the winters 1985 to 1988 is presented.

2. THE MEASURING SYSTEM
2.1 General description

The general layout of the measuring system and the main particulars of chemical tanker Kemira are presented in Fig. 1. Three frames are instrumented to measure ice induced loads on the bow, midship and aftship as defined in the ice rules.

![Diagram of Kemira with labels for frames and midship area](image)

Figure 1. Location of the transducers

The loads are evaluated with shear strain gauges applying influence technique as described e.g. in reference /10/. The shear strain gauges are connected
so that the load on the upper, middle and lower part of the frame (FTR) as well as the total load on a frame (FT) can be measured. The normal stress gauges on the frames (FN) and plating (PL) near the instrumented frames are installed to gather data on the stress level of the structure and to check the calibration of the shear strain gauges.

In the long-term measurements the data are collected and processed automatically by a microprocessor specially developed for this purpose. The microprocessor collects the data and prints it on a data cassette and paper tape twice a day.

2.2 Calibration of the measuring system

The influence coefficients for the load measuring system are evaluated with the finite element model shown in Fig. 2. Two models are developed, one for the midship and one for the bow ship. The scantlings of the aftship are quite similar to the scantlings at midship. Therefore the influence coefficients for the after frame are evaluated on the basis of the results for the midship frame.

The coefficients are determined for the case of uniform ice pressure with a load height of 0.3 m and load length of two frame spacings 0.7 m representing a continuous ice pressure on the frame. The calibration of the system is based on the assumption that the load length is usually longer than two frame spacings. If the actual load lengths are shorter than two frame spacings the system can give up to 30% too small load values. The shorter the contact between the ship and ice the larger is the error. Previous full-scale measurements have, however, indicated that the length of the contact is usually few frame spacings /6/.

![Figure 2. Finite element model for the shell structures](image)

![Figure 3. Comparison of FEM calculations to physical calibration](image)
The finite element calculations are checked by applying an inside point force on the midship and after ship frame. The point force is generated with a hydraulic cylinder and the force is measured with a force gauge, see reference /7/ for further details. The results are compared with those given by the finite element model for the case of a narrow uniform pressure on the frame as shown in Fig. 3 for the midship frame. As can be seen from Fig. 3 the results are comparable within the accuracy of about ± 10 %.

3. MEASUREMENTS
3.1 General

The measuring system was installed onboard M/S Kemira in autumn 1984. Thereafter the system has worked continuously during the winters 1985 to 1988. M/S Kemira is regularly navigating between Finland and Middle-Europe. The most common Finnish ports, where she visits, are Uusikaupunki and Kokkola. Table 1 gives the details of the measuring period and number of ice days during each winter. The ice day in this presentation means that the measuring system has encountered ice induced loads during the day. The ice days are divided according to the extent of ice navigation into various groups so that South Baltic includes the sea area south from Uusikaupunki, up to Bothnia Sea includes the sea area south from Nordsvalen and up to Bothnia Bay includes the sea area south from Kokkola i.e. it includes the total measured data.

Table 1 Measuring period and number of ice days in various winters and sea areas

<table>
<thead>
<tr>
<th>Winter</th>
<th>Measuring period</th>
<th>Number of ice days</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>South Baltic</td>
<td>Upto Bothnia Sea</td>
<td>Upto Bothnia Bay</td>
</tr>
<tr>
<td>1985</td>
<td>25.1-13.5</td>
<td>21</td>
<td>40</td>
<td>67</td>
</tr>
<tr>
<td>1986</td>
<td>1.1-8.5</td>
<td>22</td>
<td>38</td>
<td>64</td>
</tr>
<tr>
<td>1987</td>
<td>28.1-23.5</td>
<td>11</td>
<td>25</td>
<td>50</td>
</tr>
<tr>
<td>1988</td>
<td>1.1-23.5</td>
<td>–</td>
<td>10</td>
<td>30</td>
</tr>
</tbody>
</table>

The measuring system has worked successfully most of the measuring time. Few problems in the output devices have occurred and the results from the following periods are lost: 23.1-2.2.1986, 26.2-2.3.1986, 7.-21.3.1988, 23.-25.3.1988 and 28.3.-7.4.1988. These periods include about 5 ice days in the winter 1986 and 4 ice days in the winter 1988. The measuring period of the winter 1987 was shortened, because the ship spent the period 1.3 - 31.3 in harbour and in shipyard due to some repair work. In addition to the automatic data gathering
some manned voyages were performed to make observations of the environmental conditions.

As shown in Fig. 1 the measuring system covers the variation of ship's draught from 4.7 m to 7.6 m. The upper limit is due to the change of the framing system from transverse to longitudinal. The actual draught of the ship is varying from 4.0 m to 8.5 m so that the draught between 4.7 m to 7.6 m takes place during about 70% of the total time in ice.

3.2 Comparison of the winters 1985-1988 with long-term statistics

The characters of the measured winters are compared to the long-term average values. Ice formation on the Baltic starts in the northernmost parts of the Bothnian Bay in late October or early November /1/. On average, the whole Bothnian Bay has frozen by mid January and the Bothnian Sea by mid February. The ice break-up starts in the southern parts in early March and usually the northern Bothnia Bay is open again in late May. Great variations, however, occur in this process from year to year. Fig. 4 shows the probability of ice occurrence on the Baltic based on the records from years 1963-1979 /1/, Fig. 5 the maximum extent of ice during the winters 1830 to 1988 and Fig. 6 the maximum ice thickness measured outside the port of Vaasa during the winters 1920 to 1988 /9/.

Figure 4. Ice occurrence probability (%)
Figure 5. The maximum extent of ice
Figure 6. The maximum ice thickness outside Vaasa

The long-term mean value of the maximum ice thickness outside Vaasa is 52
cm and the standard deviation 10 cm /9/. Consequently according to Fig. 6 the winters 1985 and 1987 can be considered as hard, winter 1986 as normal and winter 1988 as mild. The mean maximum ice thickness outside Vaasa during the winters 1985 to 1988 is 65 cm, which indicates that on average these winters have been considerably harder than a long-term normal winter. Similar conclusion can be drawn, when the maximum ice extents are compared to the long-term mean value of 209 000 km² - the mean of winters 1985 to 1988 being 314000 km², see Fig. 5.

4. RESULTS OF THE MEASUREMENTS

The maximum values in the various load channels during measured 12 hour periods form the basic data base. Fig. 7 illustrates as an example the measured maximum values for the ice induced loads on various parts of the ship during the measured winters.

The maximum measured load value on the bow is 653 KN from 2nd of May 1985, when the ship was stuck in strongly compressing ice near Kokkola lighthouse. The second largest value is 643 KN from 10th of May 1985, when the ship hit, according to the ship's logbook, some thick and large pack ice floes. The maximum values of the winter 1985 (544 KN, 20th of April and 533 KN, 6th of February) have both occured near the Kokkola lighthouse, when the ship has been following an icebreaker in a heavily ridged ice. The maximum value from winter 1986 is 493 KN, which occured in the Bothnian Sea on the 24th of February, when the ship was ramming through ridged ice near the lighthouse Säppi.

The maximum measured value at midship is 323 KN and it occured on 26th of April 1987 during a manned voyage behind an icebreaker just before the ship was stuck in heavily ridged ice near the Kokkola lighthouse behind an icebreaker. The maximum value during the winter 1985 occured 1st of May, when the ship was stuck in compressing ice also near the Kokkola lighthouse. In that situation also one strain gauge (FPR 8 lower, see Fig. 1) was damaged due to yielding of the frame. In addition a load of 246 KN was recorded during a two and half hour towing of the ship through ice by an icebreaker on the 3rd of February and a load of value 275 KN occured during the deviation of the ship from a channel to level ice after a sharp turning of an icebreaker on the 28th of January 1987.

The measured load values at the after ship are mainly caused on the similar situations as those at the midship. The maximum value of 421 KN occured also on the 2nd of May 1985 during the compression of ice near the Kokkola lighthouse. During the compression of ice at the same place on the 1st of May 1985 a value of 362 KN and on the 3rd of April 1985 a value of 327 KN were reached. The towing of the icebreaker on the 3rd of February 1985 caused a load of
Figure 7. The measured 12 hour maximum loads on various parts of the ship
310 kN. The maximum value during the winter 1987 was 362 kN and it occurred on the 6th of February behind an icebreaker also near the Kokkola lighthouse.

The measured data is divided according to the ship's navigation area into various groups as shown earlier in Table 1. Fig. 8 gives the measured maximum values in the respective sea areas during the measured winters. Fig. 8 also gives the design ice loads according to the ice rules for the bow, midship and aftship. As can be seen the measured maximum values are higher than those given by the rules indicating also the hardness of the winters 1985 to 1988. The proper level of ice-strengthening according to the measured results is discussed in further detail in reference /8/, in which the failure probability of the frames are evaluated.

For the design purposes the effect of the distance from the waterline on the ice induced loads is important. Therefore on Fig. 9 the measured load values are plotted as a function of this distance. As can be seen the ice can cause loads down to 4-5 m below the actual waterline. The maximum loads are almost linearly decreasing when the distance increases. Above the waterline remarkable ice loads can occur as high as about 1 m above the waterline. Fig. 9 also illustrates the extent of ice framing required in the present ice rules. The extent of the ice framing seems to be adequate above the waterline, but below the waterline at mid and aftship some extensions should be considered.

![Design loads](image)

**Figure 8. The measured winter maximum values on various sea areas**

![Design loads](image)

**Figure 9. The measured 12-hour maximum values as a function of the distance from waterline.**
5. ESTIMATION OF LONG-TERM EXTREME LOAD VALUES

The statistical nature of ice induced loads is not properly known due to the
great number of affecting parameters. Consequently the extreme probability
distributions are usually used /6,12/ for evaluation of the long-term extre-
mes. The extreme distributions are in principle insensitive to the initial
distributions and can be used to analyse maximum values from constant measur-

For the evaluation of long-term extreme loads Gumbel I or Gumbel III dis-
tributions /3/ are fitted to the measured maximum load values. For the studied
cases only the measured maximum load values on various parts of the ship are
used taking no notice of the occurrence location of the load on the frame.
Consequently the effect of the draught variations on the statistical charac-
teristics of the load values is omitted. Fig. 10 shows the total measured
data base from the winters 1985 to 1988 and the fitted Gumbel I distributions
on various parts of the ship.

Figure 10. Gumbel I distributions fitted on the measured maximum load values
during the winters 1985 to 1988 on various parts of the ship.
Fig. 10 includes all the data from the measured winters and before the estimated long-term numbers can be used e.g. for design purposes the characteristics of the measured winters as described in chapter 3.2 must be taken into account. For this purpose the long-term extremes are further analysed on basis of the measured values during the different winters. Fig. 11 illustrates the results of this approach by using Gumbel extreme distributions. As shown in Fig. 11 the estimated load values according to the data from a hard winter can be about twice as large as those from a mild winter. A more detail analysis of the factors causing this difference will be the most important task in the near future so that a sound basis for determination of design ice loads from the measured results can be evaluated.

Figure 11. Long-term extremes on the basis of the measured data from different winters.

6. CONCLUSIONS

Three frames onboard the chemical tanker Kemira were instrumented to measure ice induced loads on the bow, mid- and aftship. The measuring system has worked continuously during the winters 1985 to 1988. The system has encountered ice loads during 211 days.

The winters 1985 to 1988 have on an average been considerably harder than a long-term normal winter. The maximum measured load values occurred on the 1st to 2nd of May 1985, when the ship was stuck in compressing ice near the Kokkola lighthouse.

Ice induced loads can take place down to 4-5 m below the actual waterline. The maximum loads are almost linearly decreasing when the distance from the waterline increases. The extent of the present ice strengthening seems to be adequate above the waterline, but below the waterline at mid- and aftship some improvements should be considered.
The estimated long-term load values according to the data of a hard winter can be about twice as large as estimated on the basis of the data of a mild winter. A thorough analysis of the factors affecting the level of ice induced loads must be conducted, before a sound approach for determining of design ice loads can be evaluated on the basis of the measured results.

7. ACKNOWLEDGEMENTS

The financial support of the Winter Navigation Research Board has enabled the work carried out for this paper. The author gratefully acknowledges the support. The author also owes his gratitude to the crew of M/S Kemira as this study would not have been possible without the close and fruitful co-operation with the members of the crew.

The analysis of the measured data started during the year 1986 while the author was working as an assistant in the laboratory of naval architecture and marine engineering at Helsinki University of Technology under the supervision of professor Petri Varsta. His encouraging attitude towards the work is specially thanked.

8. REFERENCES

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COLD REGION ENVIRONMENTAL TECHNOLOGY
OIL SPILL IN ICE SIMULATION MODEL DEVELOPMENT

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ABSTRACT

The simulation model concepts for oil drift in ice to be presented in this paper were developed as a part of the ESSO/SINTEF Arctic Research Program (ESARC). The work was based on a particle in fluid approach utilized previously in operative oil drift models for the North Sea and the Norwegian Sea. The work may be regarded as the first step towards an operative oil drift model for the Arctic part of the Norwegian Continental Shelf, i.e. the Barents Sea region. In the chosen approach, an oil spill is represented by a cloud of particles, released continuously during the spill period. Each particle is advected in a predetermined current field, with random motions superimposed to represent turbulent spreading. In order to account for oil weathering and entrainment by wave action, each particle is assigned a certain state, with state transitions governed by sea state, type of oil and time spent in each state. For ice infested waters, additional states have been introduced, accounting for processes such as trapping and subsequent mobilisation of oil under ice. In addition, the presence of sea ice is taken into account in the description of the velocity field.

1. INTRODUCTION

In the recent years, oil drift models operative at the Norwegian Continental Shelf have provided valuable input to environmental impact assessments and oil spill combat operations. As Norwegian petroleum activities presently are expanding North into the Barents Sea, improvements of such models are required in order to account for the possible interaction between sea ice and spilled oil. The improvements to be considered should make the model able to handle different scenarios, including oil spilled under compact ice, oil emerging in drifting ice, as
well as oil drifting into the marginal ice zone from open waters. The oil drift model should also account for variations in the ice conditions in response to temperature, wind, waves and ocean currents.

The work on these enhancements was first addressed in the ESARC project in terms of a literature review on drift and fate of oil spills in sea ice. Based on this literature review, it was concluded that the major emphasis should be given to the design of submodels for 1) Surface spreading generated by subsea blowouts, 2) Migration of oil under ice, 3) Retarded oil weathering due to cold temperature and sea ice. Oil drift in broken ice was considered as a problem mainly related to ice drift modelling. In an operative model concept, this part of the problem should be solved by an interface between an appropriate ice drift and the oil drift model. However, in the pilot model to be designed in order to test the various submodels, it was decided to include a primitive ice response model in order to represent the dynamic behaviour of the marginal ice zone (Johansen 1988a).

2. BASIC CONCEPTS

The particle in fluid approach applied in the work was imported from the operative oil drift model DOOSIM (Johansen 1987), but extended to ice infested conditions based on results from the literature survey on oil behaviour in sea ice. One of the major tasks in the present study was to formulate the various processes in submodels compatible with the particle in fluid approach. Existing models for oil spill simulation in Arctic waters have been considered (ASA 1985, Wotherspoon 1985, Comfort 1987), but none of these models completely fulfil the requirements indicated above. Thus new methods had to be derived in order to obtain an integrated approach including all the different regimes — open water, under ice, broken ice. A brief presentation of these methods will be presented in the following paragraphs.

2.1 Oil Spilled in Open Water

The main features of the particle in fluid concept, as applied to oil spills in open waters, are as follows (Johansen 1987):
- The oil spill is represented by a cloud of particles in different states, advected individually in a prescribed current field, with random motions superimposed to represent turbulent spreading.
- The initial distribution of the particles adjacent to the source depends on the spill conditions and the current regime at this site. For surface spills, the major spill condition to be taken into account is the spill rate, which together with the current regime determines the spatial extent of the spill.

- Entrainment due to wave action and subsequent resurfacing are reflected in state transitions governed by sea state, oil quality and time spent in each state.

- Evaporation is handled as a loss of particles governed by a time and wind dependent exposure parameter summed up for each particle, where the relationship between evaporative loss and exposure depends on the oil quality and the ambient temperature.

- The current field acting on each particle is represented by a set of current components, i.e. wind and wave induced drift, tidal currents and a permanent background current.

- The set of components acting on a given particle is determined by the state of the particle. Surface particles are thus influenced by both wind and wave induced currents, while wave induced currents are neglected for entrained particles.

2.2 Oil Spilled Under Ice

The major processes to be considered when oil is spilled under a compact ice cover were identified as follows:

- A major release of oil under sea ice is assumed to be related to subsea blowouts. The initial spreading of the oil under such circumstances will be governed by the radial surface flow induced by the rising gas plume.

- Oil from a subsea blowout will tend to be suspended in this turbulent radial flow. This will cause settling of oil under ice to take place over a more or less prolonged period, and thus tend to increase the under ice area initially infested by oil.

- Migration of oil settled under ice may be conceived as a series of subsequent step and rest periods, where oil droplets are resuspended by strong under ice currents, and later trapped in adjacent under-ice roughness features. Resuspended droplets are assumed to move with the water current, while trapped oil will be transported with the drifting ice cover.
- Trapped oil may be encapsulated due to ice growth. With the required data on ice growth and decay available from a dynamic sea ice model, this process may in principle be accounted for in terms of extended rest periods. However, in the present pilot model—where neither freezing or melting of ice is considered, the encapsulation process is not taken into account.

Some of the extensions identified above are also relevant for open water conditions, e.g. surface spreading of oil related to subsea blowouts. A detailed treatment of this process is given by Fanneløp et al. (1980). The other processes listed above are primarily related to ice infested regions, such as the submodels for migration of oil under ice. Concepts relevant for simulation of these processes were found in the literature related to bottom sediment transport (Yang and Sayre 1971).

The spreading of oil due to subsurface blowouts was approached by a modified random walk concept. The concept was based on the fact that this radial surface flow may be approximated as a classical source flow, where the source strength is determined by the spill conditions, i.e. the water depth at the source and the gas flow rate (Fanneløp et al. 1980). The initial random step length may thus be expressed in terms of these parameters, and subsequently reduced in proportion to the distance from source. Figure 1 shows examples of results obtained by this approach, compared with oil slick envelopes computed from source flow equations.

Settling of oil under ice is assumed to be time lagged due to suspension of oil droplets in the turbulent radial flow. The time spent in suspension, which also determines the radial displacement, is assumed to be a stochastic parameter. The probability for settling of oil under ice may thus be modelled as a stochastic process, where the probability for settling is related to the time a particle has spent in the suspended state.

Subsequent migration of oil under the ice cover is also modelled in terms of a stochastic process, governed by a probability for mobilisation related to the strength of the under ice current, and a settling probability related to the time spent in motion. The respective probability functions are fitted to empirical equations presented by Cox and Schultz (1981) for oil migration velocity under ice in response to under ice currents.
Figure 1. Random walk simulations of surface drift and spread of oil from subsea blowouts. Solid lines represent slick boundaries computed from source flow equations given by Fanneløp (1980). Only half of the symmetric plume is shown. Source depth is 100m and gas flow rate 10m³/s. A constant water current of 5cm/s is superimposed in (b).
2.3 Oil In Broken Ice

When oil is present in broken ice or outside the marginal ice zone, entrainment of oil due to wave action was identified as the major mechanism which can cause oil to migrate under the ice surface. This mechanism may however be retarded by the wave attenuation caused by broken ice, and the entrainment rate should thus be reduced with increasing ice coverage. Evaporation of surface oil is also assumed to be retarded in the presence of broken ice, and should be reduced comparatively with increasing ice coverage (ASA 1985).

The presence of a marginal ice zone will to a large extent modify the drift pattern of oil. A dense ice border, associated with on-ice winds will form a more or less compact barrier to surface oil, while a more diffuse ice border, formed during off-ice winds may be penetrated by surface oil drifting into the region as the wind turns on-ice. The oil's ability to penetrate into the ice depends to a large extent of the relative motion between surface oil and ice floes. In the present model, this difference is reflected in the choice of a larger wind drift factor for surface oil than for ice floes.

In an operative forecast system, data on ice drift velocity may be imported from a dynamic sea ice model. Meanwhile, in the present pilot model, the ice velocity field is accounted for by defining the marginal ice zone as a region of expandable broken ice in contact with an incompressible pack ice region. The border of the broken ice region towards open water is assumed to be responding as free drifting ice to wind and currents, while the inner border is coupled to the pack ice. Compaction of the broken ice border under on-ice wind is however assumed to stop as the ice coverage in this region approaches 100%.

3. PILOT PROGRAM

The present pilot model has been designed in order to demonstrate and evaluate the concepts described above for the different regimes (open water, under ice, broken ice). Results from this evaluation are planned to form the basis for implementation of the new concepts in operative oil drift models for the Barents Sea region of the Norwegian Continental Shelf. However, more detailed studies of some of the processes, which are presently handled on a more or less preliminary basis, may also be required in order to fulfil this task.
3.1 Basic Concepts

The pilot model is based on a homogeneous ocean, i.e. wind and ocean currents are spatially constant within the simulation region. Oil drift is however assumed to be modified by the presence of an ice edge, represented by a region of broken ice adjacent to a compact region of pack ice. The drift velocity of ice and oil within the broken ice region is weighted between two extremes, i.e. open water and pack ice velocities, in accordance with the local ice concentration (cfr. table 1.).

The submodels discussed above for the different regimes are unified in the model on the basis of a state transition matrix as indicated in table 2. Thus, particles representing oil spilled under ice may undergo transitions from the initial dispersed state (oil dispersed in the turbulent radial flow), into a trapped state (oil trapped in under-ice roughness features). Later these particles may change into a mobilised state, set in motion by strong under-ice currents.

Table 1. Velocity components assigned to particles in different states. Values in each column represent weights assigned to each current component. C is the local ice coverage.

<table>
<thead>
<tr>
<th>CURRENT COMPONENT</th>
<th>PARTICLE STATE</th>
<th>Surfaced</th>
<th>Suspended *)</th>
<th>Trapped</th>
<th>Mobilised**)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Background</td>
<td>1-C</td>
<td>1</td>
<td>1-C</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Tidal</td>
<td>1-C</td>
<td>1</td>
<td>1-C</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Wind induced #)</td>
<td>1-C</td>
<td>1-C</td>
<td>1-C</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Wave induced #)</td>
<td>1-C</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Pack ice drift</td>
<td>C</td>
<td>0</td>
<td>C</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

*) The term 'Suspended' is used to include both the dispersed state (particles suspended in the turbulent radial flow set up by the gas plume), and the entrained state (particles entrained by wave action).

**) The term 'Mobilised' refers to trapped particles set in motion by under-ice currents.

#) Wind and wave induced currents are represented in terms of wind drift factors, the latter accounting for near surface current shear.
Table 2. Particle State Transition Matrix. 'X' in a given element of the matrix indicates possible state transitions from one timestep to the next. The numbers (-2 .. 3) are used for cross reference.

<table>
<thead>
<tr>
<th>NEXT STATE</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R -2 MOBILIZED</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>I -1 TRAPPED</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>G 0 DISPERSED</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>I 1 SURFACED</td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>N 2 ENTRAIN</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A 3 EVAPORATED</td>
<td></td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>L</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Mobilised particles may subsequently be trapped or change into the surface state (in leads within broken ice). At a later stage, the surfaced oil may evaporate, or be entrained into the water masses by wave action. Oil in this entrained state may later resurface and be trapped under ice or arrive at the water surface, depending on the local ice coverage.

The transition probabilities for each state are in part computed from well established relations (evaporation rates, entrainment rates etc), or estimated on a more preliminary basis in terms of mean step and rest times (migration of oil under ice). Different choices of the latter parameters may be used to reflect variations in the roughness of the under ice surface. Details on the various methods are given in the Esarc Report (Johansen 1988,b).

3.2 Example Run

A scenario with oil spilled under a region of pack ice is shown as an example in the following. At the start of the spill, the pack ice region is separated from open water by an 18 km wide zone of broken ice. The depth of this zone is however changing in response to wind and currents. In order to obtain a realistic picture of the dynamical nature of this broken ice zone, actual wind observations are used (observations from Bjørnøya). Other major input data are presented in table 3.
Table 3. Input data for the example run

**SPILL CONDITIONS:**

- Source depth ........................................ 100 m
- Gas to oil volume ratio .......................... 200
- Oil spill rate ..................................... 100 tons/hour
- Oil type: Medium crude oil, density ............... 850 kg/m³
- Spill duration ...................................... 5 days

**ICE CONDITIONS:**

- Spill site located under pack ice .................. 100% ice coverage
- Distance from spill site to pack ice border ...... 7 km
- Orientation of pack ice border .................... 45°
- Pack ice velocity .................................. 5 km/day, 45°
- Depth of broken ice zone at spill start .......... 18 km

**ENVIRONMENTAL CONDITIONS:**

- Sea temperature ..................................... -1°C
- Wind observations from Bjørnøya .................... January 1988
- Background current, strength, direction .......... 12 cm/s, 60°
- Major tidal axis .................................... 25 cm/s, 60°
- Minor axis .......................................... 12 cm/s

Results at 4 and 10 days after spill start are shown at figure 2, where the location of the spill site is indicated by the crossing of the horizontal and vertical line in the plot, while the oil distribution is indicated by markers representing the particle cloud released during the spill period. The different marker symbols represent the state assigned to each particle, as designated in the mass budget shown to the right.

Since the spill source is located in the pack ice region, oil from the subsea blowout will initially reach the under ice surface. The pack ice is however assumed to move with a constant velocity of 5 km/day in a direction parallel to the ice border. Thus oil trapped under ice will be advected away from the spill site.
Figure 2. Output from the example run. Oil distribution 4 and 10 days after start of the spill. Large markers at the axis represent 10km. The spill site is marked by the crossing of the vertical and horizontal line. Lines at 45° inclination are respectively the pack ice border (upper line) and the broken ice border.
The extensive spreading of the oil under the pack ice is in this case to a large extent caused by mobilization of trapped oil by tidal currents. If the pack ice region had been assumed to move with the tides, the current shear at the under ice surface would have been reduced significantly, and the oil would have tended to stay trapped in under-ice cavities for longer periods.

Results from ice floe tracking experiments in the marginal ice zone in fact indicate that this is a likely situation in the marginal ice zone, where the unconsolidated ice is found to be closely coupled to the tidal currents in the underlying water masses (Johansen et.al. 1988). To what extent internal ice stresses will reduce this coupling in the interior pack ice is more uncertain (Johannessen et.al. 1983).

4. CONCLUSIONS

The pilot model for oil drift and fate in ice infested regions may be conceived as a first step towards an operative oil drift model model for environmental impact assessments and oil spill combat management in the Arctic region of the Norwegian Continental Shelf.

A more detailed study of relevant theoretical and experimental work on the behaviour of oil in sea ice will certainly be required to reach this goal, but the basic concepts are believed to represent an efficient and flexible basis for further improvements.

5. REFERENCES


WATER CONSERVATION AT THE SWEDISH ANTARCTIC
WASA BASE - IMPLEMENTATION AND RESULTS
1988/89

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ABSTRACT

During the 1988/89 summer season a Swedish base was built at a nunatakk in the Norwegian sector of the Antarctic. The base consists of a dwelling house and a machine building, with comfortable facilities for 10-12 people. The dwelling house is equipped with in-door running hot and cold water and fitted with a washing machine, a dishwasher, showers and dry toilets. All taps and machines are the latest on the market, and have good capacity for water conservation.

Water conservation is in this case of great interest. The reason is two-fold: reduced specific consumption gives increased in-house capacity for the dwelling house and simultaneously diminishes the environmental impact of effluent wastewater.

The specific water demand for 1988/89 summer season was 38 litre/person and day. Of that 37 % was connected to the kitchen, 24 % to the showers and sauna and 26 % to the laundry facilities. In the coming seasons further reduction can be obtained by fitting aerators on the taps and installing temperature controlling devices for inlet hot and cold water. It should then be possible to lower the figure below 35 litres/person and day.

1. INTRODUCTION

During the last decade Sweden has developed a new interest in arctic and sub-arctic engineering. In parallel Swedish scientific research in these areas has widen, with expeditions like YMER 80 to Artic regions and the 1987/88 Antarctic expedition to Dronning Mauds Land.

The latter expedition was followed up by a larger expedition in 1988/89, with a scientific and an engineering research program. The latter program consisted of a permanent summer base erected on a nunatakk and creating a monitoring program for sanitary and building research.
2. GENERAL DESCRIPTION

The base is erected on a hill slope on the nunatak Basement in the mountain chain Heimefrontfjella. The hill consists of a permafrost moraine. WASA consists of two separate buildings, the main building with full living facilities for up to 12 people and a secondary machine building with diesel generators, a water treatment unit, storage space for food and spare parts etc. The general view is shown below.

Figure 1. WASA base. Longitude W 13° 21', latitude S 73° 03'.

The machine building was assembled from three prefabricated steel containers, whereas the main building was built using normal Swedish techniques for wooden constructions with glass-fibre insulation.

Both buildings are placed on open metal foundations, with a distance to the ground of 1.4 - 1.8 meters. The open construction is to prevent snow from accumulating on the lee side of the buildings.

The buildings are connected with a utilidor, containing hot and cold potable water and the main power line.

3. WATER CONSERVATION.

Sanitary installations in remote areas often tend to create operating problems, as Hanaeus and Ham (1987) have shown. Water conservation reduces both the specific use of potable water and the production of wastewater,
thus often reducing operation and maintenance problems to acceptable levels. Flow-reduction hardware is described by Baker et al (1975) and by Morgan and Pelosi (1980). Sletten and Reed (1988) state that present daily per capita use of water at US Antarctica stations varies between 79.5 litre (the Pole station) and 212 litre (the McMurdo station).

When it comes to navy operations, potable water tend to be a chronic problem; according to Schatzberg et al (1980). It was concluded that installation of minimum-flow plumbing could reduce use of water with > 50 %. Siegrist (1983) considers a total saving of between 50 and 90 % possible in American homes, motels and restaurants.

Thus water conservation is generally of interest where the supply of potable water is scarce, or treatment of wastewater profits from lowered specific volumes.

4. WATER AND SEWAGE SYSTEM.

Potable water is provided from a water melting and storage unit in the machine building. During the construction phase it was assumed that water was only available as snow or glacial ice. A system was therefore constructed, with a capacity of melting approx. 1400 kg ice or snow per 24 hours. The system consists of a melting chamber with three fixed spraying nozzles, a recirculating pump for water and a water heating reservoir with a total power of 6,75 kW.

The water pipes in the utilidor connecting the buildings, are prevented from freezing with heat insulation and separate heating cables. The heating cables are thermostatically controlled and with an output of 10 W/meter.

The water system in the main building is concentrated to a "wet" area, to simplify the construction and minimize the work of emptying and refilling it at the beginning and end of the season.

As shown in the figure below, a total of seven sanitation units are connected to the cold and/or hot tap pipes. The inlet cold water pipe first passes an internal container intended as a reserve in case of system failure.
In order to minimize water consumption the latest domestic technology in water conserving units was used. This was for two reasons. In the first place melted water was believed to be a scarce resource when there were many visitors; thus conservation is necessary to avoid shortage of water. Secondly a minimized consumption of tap water is closely linked to lowered volume of sewage.

This is positive, both with regard to environmental impact and strategies of sewage purification. For a start it was decided only to produce grey water. To achieve this no flush toilets were installed. Instead two dry toilets, with separate ventilation and external refuse, were integrated in the main building.

The nominal water demand for each tap point is shown below. The taps at the laundry, kitchen sink and wash-basin have an internal regulator for maximum flow and maximum temperature of hot tap water. They are preset with a screw-driver, and can easily be adjusted.
Table 1. Nominal tap and machine water demand, WASA base.

<table>
<thead>
<tr>
<th>Source</th>
<th>Demand 1/min.</th>
<th>Units</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shower heads</td>
<td>6-8 - 6-30</td>
<td>2</td>
<td>max. flow independent of pressure.</td>
</tr>
<tr>
<td>Taps</td>
<td>3-</td>
<td>3</td>
<td>adjustable max. flow/temp.</td>
</tr>
<tr>
<td>Washing machine</td>
<td>68-100</td>
<td>1</td>
<td>capacity 4 kg dry laundry.</td>
</tr>
<tr>
<td>Dishwasher</td>
<td>23</td>
<td>1</td>
<td>capacity 14 place-settings</td>
</tr>
</tbody>
</table>

The showers are equipped with thermostatic taps and heads with hydraulic flow-control devices. The washing machine and dishwasher are for domestic purposes, chosen because they were the most water saving ones on the market.

Water from all taps and machines is gravity-fed to a single outlet point in the shower room. The sewage system leading to the recipient consists of 75 mm inner diameter polyethylene pipes with rubber sealings. The pipes are held in place and kept at a constant slope by a supporting wooden groove. About 100 metre downhill the grey-water is deposited in a shallow snow and ice layer.

5. FIELD EXPERIENCES AND RESULTS

Normal Swedish domestic consumption of tap water today averages 200 litre/person and day. Of that approx. 30 % is lost on the way from producer to the single household, consequently 140 litres/person and day can be seen as a net value. This figure can be greatly reduced without lowering the sanitary standard, or putting excessive constraints on the users. With reference to findings reported by Sletten and Reed (1988) it was believed that specific consumption for WASA base would not exceed 50 litres/person and day.

During the first three weeks of work at the base site, people directly connected to the building activities as well as researchers lived in tents, caravans designed for the purpose and glass-fiber moulded huts. The total number of people in the area varied between 9 and 24, depending on the research activities.

After a few days at the base, an area with a mix of water and ice was found down at the adjacent glacier. All water was then taken from that source. The water was during this first period stored in 50-litre plastic
containers. Apart from being used for cooking and cleaning kitchen equipment, a small amount was used for personal hygiene.

No exact measurements were possible to be made during this period, but it can be estimated that the daily use of water was in the range of 5-10 litres/person and day. During this period no piped water was available, and hot water had to be heated on bottle-gas stove.

After two weeks in the area, a simple shower-tent was erected. With the aid of a handheld shower device and protected from the wind, it was possible to take a shower with a minimum use of water. The normal use was between 4 and 6 litre of hot water.

After three weeks of construction time it was possible to move into the main building. For the rest of the period all preparing of food, personal hygiene, washing etc. was done in the building.

In order to split the total dwelling house consumption of potable water into more specific parts, totally eight water meters were installed. They were equipped with sensors for remote logging of flow.

The specific water demand as logged varied between 19 and 58 litres/person and day, as shown in Table 2.

Table 2. Specific and total water demand for WASA base, 24/1-1/2 1989.

<table>
<thead>
<tr>
<th>Value</th>
<th>Water demand, litres/person and day</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total</td>
</tr>
<tr>
<td>Mean</td>
<td>37,8</td>
</tr>
<tr>
<td>Max.</td>
<td>57,7</td>
</tr>
<tr>
<td>Min.</td>
<td>18,9</td>
</tr>
<tr>
<td>Mean %</td>
<td>100</td>
</tr>
</tbody>
</table>

During the measuring period all linen was washed, giving in all 13 washing cycles and a total water use of 1020 litres. If this figure is excluded from the grand total, the mean total goes down to 30.7 litres/person and day.

6. CONCLUSIONS

Water conservation with commerciably available taps, shower heads, machines etc. can reduce normal in-house use to a great extent. With full sanitary standard, except for flush-toilets, the specific water demand was well below 40 litres/person and day. Because of the short in-house living period the use of the washing facilities were intensive. It can therefore
be presumed that normal specific water use at Wasa base during longer periods, is below 35 litres/person and day.

It is essential to avoid excessive use of tap water due to flushing away too hot cold water or too cold hot water. Both cases can occur, and should be avoided by careful technical planning.

Additional water saving can be achieved by installing areators on the taps, and temperature controlling devices at the inlet side of the main hot and cold water lines.

7. ACKNOWLEDGEMENTS

This research was done as a part of the 1988-89 Antarctic program supervised by the Swedish Polar Research Secretariat. Fundings for 88/89 were allocated by COLTTECH (Board of Directors of Luleå University of Technology) and STU (The National Board for Technical Development).

8. REFERENCES


POLLUTION-FREE PETROLEUM PRODUCTION
AND TRANSPORTATION
SYSTEMS IN THE ARCTIC REGION

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ABSTRACT

This paper describes advanced process technologies and the implementation of environmental systems for designing production facilities that will maintain pollution-free environments and eliminate all wastes to accomplish zero discharge in the Arctic. It presents original methods for transporting petroleum gases and liquids in all combinations by subsea tanker all year around. The paper also describes the elimination of flaring of associated petroleum gas. Further, if fuel gas contains hydrogen sulfide (H₂S) and carbon dioxide (CO₂) is to be used for power generation, special treatment of the fuel gas is described to remove pollutants, followed by final treatment of flue gases to remove trace emissions of SOₓ and NOₓ to the atmosphere. This paper also deals with new technologies for support and utility facilities including the handling of solvents and drilling fluids and the treatment of various waste fluid streams. New systems such as double containments with leak-detection devices, closed loop, and recycle systems are described to prevent oil leakages and unnecessary emulsion formations.

1. PETROLEUM PRODUCTION

In the United States alone, the Alaska North Slope area contains some 19 billion barrels of proven and estimated reserves. The northern Canadian Islands contain estimated reserves of over 35 billion barrels. These reserves represent only U.S. and Canadian sources, excluding other Arctic Region countries.
First, in view of the harsh Arctic environment, production facilities will be equipped with only the necessary production units while the remainder of the downstream process units are located in non-Arctic regions. Second, different production methods may be utilized, two of which are described below. These methods take into account the thermodynamic properties of natural gases: that compressed vapors above the critical points behave like compressible fluids with densities close to liquid. The compressible fluids, vapor densities, and weight ratios of liquid to natural gas mixture are illustrated in Figures 1 and 2, respectively.

1.1 Crude Processing - Arctic Oil and Gas Field

Under a simple treatment scheme, shown in Figure 3, two stages of separation are used to stabilize the oil. The production from wellheads is heated before entering the high-pressure separation unit where the bulk of the associated gas is first separated, then compressed to medium pressure of 4500 to 5000 psia. (This pressure level is very commonly used in the petroleum and chemical industries.) A small portion of the compressed gas is used as fuel for power generation. After separation of the free phase of water, the crude is dropped in pressure to the second-stage separators which operate at 2 to 5 psig, resulting in a three-phase separation. Any crude which still contains emulsified water is then transferred into a dehydrator. The flashed gases are compressed and mixed with high-pressure separation gases. The dehydrator utilizes electrostatic treatment to assist in the coalescence of water droplets, which facilitates the separation. The heating source is flue gas exhausts from power generation gas turbines.

After the water removal step, the crude is pumped to a specially designed subsea tanker. Natural gas above the critical conditions is also transferred in bulk at 4500 to 5000 psia.

1.2 Petroleum Gas Processing - Arctic Gas Field

By employing a simple single-stage separation process, shown in Figure 4, the bulk of gases are separated and compressed to medium pressure of 4500 to 5000 psia. A small portion of the compressed gas is used as fuel for power generation.

Petroleum condensate and gas above the critical conditions are then also transferred to a specially designed subsea tanker.
2. **PETROLEUM TRANSPORTATION SYSTEM**

A unique method is presented for transporting petroleum liquids and gases or a combination of both gases and liquids (partial or stable crude oil) in sea ice Arctic conditions during all-ice seasons.

In moving oil and gas from the Arctic region, a subsea tanker will present less of a hazard to the Arctic environment, primarily because it will avoid the threat of rupture by sailing under and clear of sea ice. The problem posed by a massive oil spill from a tanker on Arctic sea is at least as great as that from a pipeline rupture. It must be assumed that oil from such a spill would reside in the region for an extremely extended time. Because of the lack of evidence thus far for scientific evaluation of the bio-degradation of oil in ultracold seawater, the effects can be assessed only speculatively.

Polar ice caps, which inhibit surface ship transport, and the operating cost of the Arctic icebreaking tankers now used are strong arguments in favor of the more efficient subsea tanker. The recent Valdez oil spill and its severe environmental effects, both current and long-term, provides another strong argument.

Arctic sea ice conditions require that the Arctic rigid icebreaking tankers presently used do the job the hard way—on the surface. Arctic sea ice conditions are neatly set aside by the subsea tanker which will do the job the submerged way. A new concept in subsea transportation is presented, as shown in Figure 5.

The subsea tanker is compartmented into three distinct modules:

- Petroleum oil and gas
- Petroleum condensate and gas
- Petroleum crude oil

The compartmentalization system is flexible in order to store the petroleum fluids in any of the modules and is also designed to maintain the gases above the critical conditions of 4500 - 5000 psia for easy transportation without expensive cryogenic requirements.

The cargo capacity for a 156,000-dwt subsea tanker operating in the Arctic is more than 80% of the displaced volume of the ship. The biggest advantage of this fact is that if leakage developed in the subsea tanker, it can be contained.

The subsea tanker can also be used in conjunction with sea-going surface tankers with a similar arrangement as described in the subsea
3. POWER GENERATION, FLUE GAS TREATMENT, AND MAJOR UTILITIES

Gaseous Fuel. If the associated gas (methane, ethane, etc.) is used for power generation and contained hydrogen sulfide (H₂S) and carbon dioxide (CO₂), then the required amount of natural gas is amine-treated, followed by zinc oxide treatment for any trace removal of hydrogen sulfide. Such fuel is normally used for power generation for production facilities.

Liquid Fuel. Methanol is the most logical fuel for producing power in the Arctic region. It is stable, easily transportable, and has absolutely no sulfur and nitrogen base compounds. With small modifications, gas turbines can operate on dual fuel systems.

4. FLUE GAS TREATMENT - DOWNSTREAM PROCESSES

The exhaust gases exiting a combustion chamber consist of carbon monoxide (CO), partially burned hydrocarbon (PHC), NO₂, and SOₓ, all products of combustion, along with remaining atmospheric gases. Figure 6 illustrates various treatment processes. Steam is injected into the combustion chamber of the gas to reduce the NOₓ level by lowering flame temperature, resulting in higher CO content in the turbine exhaust gas.

5. HYDROCARBON OXIDIZER AND CO CONVERTER.

The partially burned hydrocarbon (PHC) and residual CO are converted to carbon dioxide and water in the presence of CO catalyst, which promotes the following chemical reactions:

\[
\text{PHC} + \text{O}_2 \xrightarrow{\text{Catalyst}} \text{CO}_2 + \text{H}_2\text{O} \quad (1)
\]

\[
\text{CO} + \frac{1}{2}\text{O}_2 \xrightarrow{\text{Catalyst}} \text{CO}_2 \quad (2)
\]

To promote a high rate of gas contact with a catalyst surface, the converter is designed to have either a monolithic or honeycomb structure.

6. SELECTIVE CATALYST REDUCTION (SCR) SYSTEM

In the SCR system, ammonia as a reducing agent is injected in the exhaust gases in the presence of catalyst to reduce NOₓ, as demonstrated in the equation:
The NO_{x} removal efficiency is governed mainly by flue gas temperature, NH_{3}/NO_{x} mole ratio, and catalyst volume. The optimum temperature for SCR operation is between 282°C to 404°C. The catalyst has the characteristic of oxidizing SO_{2} in the flue gas to SO_{3}.

7. CATALYTIC OXIDATION

Sulfur dioxide (SO_{2}) is converted into sulfur trioxide by means of a special sulfur-resistant catalyst which promotes the oxidation process at 200 to 250°C. A supplement fuel is not necessary for this process.

8. ACID GAS SCRUBBER

The acidic gases, primarily SO_{2}, CO_{2}, and traces of SO_{3}, NO_{2}, if any, are water-scrubbed followed by scrubbing with a dilute hydrogen peroxide (H_{2}O_{2}) solution.

\[ \text{SO}_{3} + \text{H}_{2}\text{O} \rightarrow \text{H}_{2}\text{SO}_{4} \]  \hspace{1cm} (4)

\[ \text{SO}_{2} + \text{H}_{2}\text{O}_{2} \rightarrow \text{H}_{2}\text{SO}_{4} \]  \hspace{1cm} (5)

\[ 2\text{NO}_{2} + \text{H}_{2}\text{O}_{2} \rightarrow 2\text{HNO}_{3} \]  \hspace{1cm} (6)

High concentration of sulfuric acid is produced, which can either be used internally or exported. The vent gases from the scrubber that contains only CO_{2} are discharged to the atmosphere. If desired, CO_{2} can also be recovered as liquefied gas or CO_{2} ice.

The excess concentrated acid can be neutralized with magnesium hydroxide Mg (OH)_{2} to produce stable salt for safe disposal.

\[ \text{H}_{2}\text{SO}_{4} + \text{Mg(OH)}_{2} \rightarrow \text{MgSO}_{4} + 2\text{H}_{2}\text{O} \]  \hspace{1cm} (7)

\[ 2\text{HNO}_{3} + \text{Mg(OH)}_{2} \rightarrow \text{Mg(NO}_{3})_{2} + 2\text{H}_{2}\text{O} \]  \hspace{1cm} (8)

With the implementation of these technologies, absolutely pollution-free environmental conditions can be achieved.

9. NITROGEN GAS GENERATING SYSTEM

The nitrogen gas generating system provides an air separation process which traps the oxygen molecules in compressed air by using special
alternating beds of these adsorbents are exposed to compressed air in a cyclic process of adsorption and desorption. Oxygen is rejected and vented into the atmosphere through a nitrogen purge containing 30% oxygen, which can utilized in other process units as enriched oxygen air.

The system consists of three basic modules as shown in Figure 7. Along with its other uses, nitrogen can also be used to transfer fluids, thus eliminating pumps, their maintenance, and the possibility of leaks and drippings.

10. FRESH (DESALINATED) WATER SYSTEM

The feed water is fed through a plate type exchanger and preheated by outgoing distillate and blowdown. In multiflush evaporation systems, vapor generated in each stage or effect is used as the heating steam for each succeeding effect.

The vapors from the last effect are compressed and used as a heating source to the first effect. The combination of vapor compression with a multiflush evaporation system requires only 40 - 60 Btu per pound of water production.

11. PRODUCED WATER TREATMENT

Systems similar to the fresh water system described above can be used. Advantages would be:

a. Compact system; no bulky tanks and transfer systems.
b. Elimination of flotation unit and chemicals.
c. Less space needed.
d. Recycled water for secondary recovery, if desired.

12. EMULSIONS and HYDROCARBON LIQUIDS TREATMENT: CLOSED LOOP RECOVERY AND RECYCLE SYSTEM

Wastewater is collected from various unit operations in an equalization tank from which free-floating oil and settleable solids are removed.

As illustrated in Figure 8, the remaining wastewater is transferred to a process tank. From the process tank, wastewater is pumped and recirculated through the membrane modules. Wastewater is continuously added to the process tank for treatment.
In a continuous process design, the wastewater feed is progressively concentrated as it is pumped from stage to stage, exiting from the membrane module system at final concentrations.

Water and low molecular weight solutes pass through the membrane pores and are removed as permeate. Emulsified oil cannot pass through the membrane pores and also separates the emulsion into oil and water.

The permeate water is steam-stripped to remove any entrained oil and then returned to the process tank while the clean water is recycled to the process unit, resulting in zero discharge to the environment.

The advantage of this system is that chemicals and additives additions are eliminated.

13. HYDROCARBON VAPOR ABATEMENT SYSTEM

The containment air streams are preheated in the heat exchanger by the hot exhaust released from the catalyst as shown in Figure 9. Gases pass through the heater to the catalyst where combustion takes place. At the heart of the system is a platinum-coated catalytic element. The unit operates at temperatures sufficiently high to destroy organic contaminants. Special ceramic insulation retains the heat, which is recovered during the process and recycled to preheat the inlet gases. Reusing the energy greatly reduces operating costs. This system destroys aliphatic and aromatic hydrocarbons completely. The clean vapor effluent, consisting of carbon dioxide, water, and remaining air components, is discharged after being cooled to the atmosphere.

14. STORAGE OF CHEMICAL SOLVENTS AND SAFE HANDLING OF SECONDARY CONTAINMENT SYSTEMS

Accidental spills and leakages are deleterious to the environment, including in damaging consequences of sea and ground water contamination in both exposed and unexposed areas.

By implementing the secondary containment concept, many industrial chemicals, including solvents, drilling fluids, acids, leaks, mixtures, and wastewater, can be safely stored and transported between the process units to storage tanks and to treatment facilities.

The piping system comprises an inner "carrier" piping system assembled with a fully pressure-rated, outside "containment" pipe. The containment pipe is used to safely contain any fluids leaking from the carrier pipe.
Two major leak detection systems are popular in secondary containment systems. Either could be readily adapted to the proposed containment concept:

a. Cable Detection systems

b. Electrode detection systems

Cable detection systems are highly accurate in their ability to detect leaks and to locate them precisely.

The simplest, liquid-sensing electrode leak detection involves sealing off finite zones of secondary containment piping and installing a saddle with a tap into the containment space of each zone. A detection device installed into this tap can be used in a variety of ways to detect leaks.

15. EFFECTS OF POLLUTION ON ECOLOGY

Increasing scientific evidence shows that emissions of pollutants from the combustion of fossil fuels contribute to air pollution and that polluted air is harmful to human health and welfare and to the environment. Such phenomena as acid precipitation and ozone depletion in the upper atmosphere with formation near ground level together with their effect on the earth’s natural resources have emerged as the premier environmental issues currently facing the industrialized countries.

Water pollution produced by oil spills and solvents can also contaminate the waterways and oceans, thus affecting marine life and destroying some species.

16. INORGANIC GAS DISCHARGE.

Carbon dioxide is not considered a pollutant; however, there is concern that excessive quantities of this gas within the atmosphere might produce a "greenhouse effect" causing the gradual warming of the planet and changing the global climate. Many of the inorganic and organic gas discharges have been found to be injurious to plant, animal, and human life.
Described below are products of combustion and their effects on the environment, including human and other living organisms.

**PRODUCTS OF COMBUSTION**

**OXIDES OF CARBON**

<table>
<thead>
<tr>
<th>Name</th>
<th>Formula</th>
<th>Effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Monoxide</td>
<td>CO</td>
<td>Danger to human health; ability to pass through lungs directly into the bloodstream of an organism.</td>
</tr>
<tr>
<td>Carbon Dioxide</td>
<td>CO₂</td>
<td>Absorbs heat energy and may produce a &quot;greenhouse&quot; effect.</td>
</tr>
</tbody>
</table>

**OXIDES OF NITROGEN**

<table>
<thead>
<tr>
<th>Name</th>
<th>Formula</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrous Oxide</td>
<td>N₂O</td>
<td>(Laughing gas) Inert, not a pollutant</td>
</tr>
<tr>
<td>Nitric Oxide</td>
<td>NO</td>
<td>Main product of combustion, considered harmless by itself. Converts to NO₂. Some indication that it may disintegrate the ability of red blood cells to carry oxygen.</td>
</tr>
<tr>
<td>Dinitrogen Trioxide</td>
<td>N₂O₃</td>
<td>Unstable, rare, not a significant pollutant.</td>
</tr>
<tr>
<td>Nitrogen Dioxide</td>
<td>NO₂</td>
<td>Causes significant effects in the atmosphere, e.g., forms smog, yellows white fabric, creates plant leaf injury, reduces plant yields.</td>
</tr>
<tr>
<td>Dinitrogen Pentoxide</td>
<td>NO₂O₅</td>
<td>Unstable, rare, not a significant pollutant</td>
</tr>
</tbody>
</table>

**OXIDES OF SULFUR**

Sulfur is released into the atmosphere from burning processes in the form of sulfur dioxide and sulfur trioxide.

<table>
<thead>
<tr>
<th>Name</th>
<th>Formula</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sulfur Dioxide</td>
<td>SO₂</td>
<td>Sulfur dioxide will slowly oxidize to sulfur.</td>
</tr>
</tbody>
</table>
Sulfur trioxide is highly soluble in water and forms sulfuric acid. Studies have found a link between \( \text{SO}_3 \) and the occurrence of lung cancer.

Sulfur oxides are considered significant pollutants. They will spot and bleach leaves of plants and trees. Snow or rain will wash sulfur oxides from the atmosphere; however, the rain will turn acidic. Acid rain is increasingly of concern because of its detrimental effect on plant life.

17. ORGANIC GAS DISCHARGES

The majority of organic gaseous discharges into the atmosphere occur from natural sources. Of the many organic discharges from industrial sources, the more significant ones are:

- Oxygenated hydrocarbons
- Halogenated hydrocarbons
- Hydrocarbons, such as paraffins, olefins, and aromatics

Most of the chemicals in these categories are carcinogenic, which generate odors, may be highly reactive, readily combine with other elements of the atmospheric environment to produce ozone, and create additional significant danger to life and comfort.

18. MAINTAINING A POLLUTION-FREE ENVIRONMENT IN THE ARCTIC REGION

A pollution-free environment in the Arctic can be accomplished by adopting the following steps:

- Installation of minimum production facilities.
b. Elimination of natural gas flaring or venting directly to the atmosphere.

c. Not building natural gas conversion plants. The investment costs of such plants will be considerably higher because of harsh climate design factors. Operational costs will more than double. In addition, such plants require much more energy to operate in the Arctic, and the costs of environmental control are astronomical.

d. Secondary containment to contain liquid spills.

e. In-place destruction of vapor and liquid hydrocarbons to harmless emissions.

f. Implementation of pollution control technologies and monitoring systems.

It would be cheaper for mankind to pay the economical price to maintain a pollution-free environment today than to face irreversible life-threatening ecological consequences tomorrow.

19. REFERENCES

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May 2-5, 1977.
GENERAL OVERVIEWS
DIPOL ACTIONS
IN THE FRENCH POLAR TECHNOLOGY

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Engineering and R & D
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Michel HUTHER
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Development Center, Chairman of DIPOL

ABSTRACT

DIPOL, a French group for the Development of Industries in POLar regions, is presented.
The main topics of the DIPOL R & D programme are :

. site analysis (geotechnical and environmental)
. ice-structure interaction
. materials
. ships
. structure concepts (onshore and offshore)

The site analysis relates to the atmospheric conditions, the iceberg occurrence distribution, the iceberg behaviour during impacts, the soil modelling taking into account the salt migration, and the structure of an artificial stone breakwater.

In the material programme, the correlation between the external and internal temperatures of steels and composite materials is studied. The long term behaviour of concrete and composite materials exposed to the harsh environment of the Antarctic has also been experimented.

With respect to steels and ships, the project aims to develop a new Arctic steel and to optimize the structure and form of a large merchant ice-breaker.

Concerning structure concepts, 3 offshore projects are briefly described :

. 2 gravity base concrete structures designed for use in frozen seas
1. INTRODUCTION

Although the recession which has plagued the oil industry for several years worsened with the sharp drop in crude oil prices in 1986, oil companies have continued to pursue exploration activities in the Beaufort Sea off the coasts of Canada and the United States.

An important gas development is also foreseen on the far-east of the USSR, off the coast of Sakhalin Island.

In both cases it will be necessary to develop offshore drilling/production installations and means of transportation by sea.

In addition, France owns and operates a scientific base in Terre Adélie in which numerous studies and experimental researches on polar environment and ice behaviour are performed.

For these reasons, significant research and development studies have been undertaken for several years, in the field of Arctic technology, by French companies, institutes and laboratories.

In order to coordinate and enhance these works, it has been decided to create the DIPOL group (French group for the Development of Industries in POLar regions).

2. DIPOL : ORGANIZATION AND ACTION

2.1. Objectives

The primary objectives of the DIPOL Group are the following:

• to favour the coordination of actions and projects in progress,
• to organize exchanges of scientific and technological information on completed works of Research and Development,
to maintain a current list of the actions and projects in progress and under preparation,
• to annually actualize the documentation about the polar potential market,
• to initiate future actions and assist the Members of the Group in their organisation and in the search for financing,
• to ensure the external transmittal of information about the Members' activities in the polar field,
• to coordinate cooperation on an international level between R & D groups.

In particular, concerning this last action, DIPOL is the French interlocutor of the Canadian Department of External Affairs for scientific cooperation in the Arctic technology.

2.2. Members

DIPOL gathers several French companies, institutes and organisations whose specialities are often complementary:

• Company Alsthom-Chantiers de l'Atlantique,
• Bouygues Group - Company Bouygues Offshore (BOS)
• Bureau Veritas (BV)
• Institut Français du Pétrole (IFP)
• Institut de Recherche de la Sidérurgie Française (IRSID)
• Laboratoire Central des Ponts et Chaussées (LCPC)
• SOLLAC GTS/TFK Companies
• Compagnie Nationale de Navigation (CNN)
• IFREMER
• Société de Dragage International

Several associated members also involved in the DIPOL activities include:

• Centre National de la Recherche Scientifique (CNRS)
• Ministère en charge de la Recherche
• Territoire des Terres Australes et Antarctiques Françaises (TAAF)
• Expéditions Polaires Françaises
2.3. Specialities

The DIPOLO Group is managed by a Pilot Committee whose secretariat is held by Bureau Veritas.

It includes five Committees of Speciality:

- Polar Environment
- Soils and Rocks in Polar Conditions
- Ice-Structure Interaction
- Materials for Cold Regions
- Structure Concepts (onshore and offshore)

Each Committee of Speciality

- carries out the progress report of the projects and of the international interactions and reports its findings to the Pilot Committee Representative,
- submits to the Pilot Committee the new projects which could be included in the Group activities and the nomination of new members,
- issues the list of the anticipated studies and cooperation projects,
- defines the objectives and priorities which are to be submitted to the approval of the Pilot Committee,
- organizes technical meetings among the Members,
- in cooperation with the Pilot Committee, assists the Members in organizing their actions and in finding the necessary financing and logistics.

Such an organisation allows exchanges and cooperation between the leading specialists on a specific topic, thereby optimising their activities. The information relating to the actions of one of the Committees of Speciality is transmitted to the others through the Pilot Committee.

3. R & D IN PROGRESS

About a dozen research projects are in progress under the cooperation of DIPOLO Members. These projects, for the purpose of the presentation, are grouped in four topics:
...site analysis, covering the activities of two committees of speciality (Polar Environment - Soils and Rocks in Polar Conditions), materials (Materials for Cold Regions), ships (Ice-Structure interaction - Structure Concepts) offshore platforms (Ice-structure interaction - Structure Concepts)

3.1. Site Analysis

The studies under completion aim to provide the designers with a better knowledge of the definition of the environment in polar regions, Arctic and Antarctic, and of the behaviour of natural materials as soils and rocks.

A first action, planned on two years, concerning the Canadian Arctic environment, is presently in progress under the cooperation of Beneteau Shipyard, Bureau Veritas, Kurbiel Expéditions and IFREMER and with the sponsorship of Ministère de l’Industrie. The support is provided by the two sailing ships Vagabond’eux and Tupperware/Vagabond 3 of Kurbiel Expéditions. During the summer 1988, the steel ship Vagabond’eux navigated the North West passage from Pacific to Atlantic Ocean after which the Vagabond 3, a composite ship built by Beneteau, joined her at the exit of the Bellot Channel after passing through Resolute Bay. During the trips, the ship crews studied the atmospheric and ice environment. The programme was concerned with the analysis of the conditions in which are observed the phenomena of mirages, "polynias" and ship structure icing. During the navigation of Baffin Bay and Davis Strait, a detailed observation of icebergs was carried out. The collected data are under analysis but it can already be said that mirages are more frequent than thought, as, generally, crews are not always conscious of the phenomena's occurrence. A complementary study is planned concerning the wind structure, i.e. wind speed distribution for various meteorological conditions.

Another work is under way in the Antarctic with the participation of Territoire des Terres Australes et Antarctiques Françaises (TAAF), Ecole Nationale des Ponts et Chaussées, Laboratoire Central des Ponts et Chaussées (LCPC), Institut Français du Pétrole (IFP) and Bureau Veritas. Analysis and measurements are being conducted to better define the sea
ice, the temperatures, the ice and iceberg actions on coast protections and the behaviour of an artificial embankment. Studies are performed in cooperation with the Canadian company C-Core and the sponsorship of the Ministère en charge de la Recherche.

The embankment survey involves the movements of the rocks which form the slope exposed to wave and ice actions, and the measurements of temperatures and ice concentration in the center part. Holes have been drilled to carry out the measurements of temperatures, electrical characteristics, diagraphy and endoscopy.

\[
\begin{align*}
\text{Conductivity} & \quad \text{Dielectric constant} \\
\text{Ice} & \quad 5^\circ C \\
\text{Water} & \\
\text{Ice} & \quad -20^\circ C \\
\text{Ice} & \\
\end{align*}
\]

\[10^6 \text{Hz} \quad 10^7 \text{Hz} \quad 10^8 \text{Hz} \quad \text{Frequency} \]

**Figure 1.** Dielectric constant and conductivity versus sound wave frequency

Data obtained from thermistors were used to display isotherms, to observe temperatures and ice extensions since December 1986. Capacity and resistivity measurements allow the differentiation between water and ice. Measurements are performed with 3 frequencies: 0.1 kHz, 1 kHz, 10 kHz. Variations are shown in Figure 1.

As a complement to studies on sites, a research programme is conducted in laboratories involving the Laboratoire de Géomorphologie de Caen (CNRS), the Laboratoire d’Aérothermique de Meudon (CNRS) and the Laboratoire Central des Ponts et Chaussées (LCPC) with the support of the Ministère en charge de la Recherche.

This programme, including theoretical studies and laboratory tests, aims to determine a representation of the
rupture of rocks submitted to frozen cycles. This phenomenon is of importance when considering the lifetime of embankment built with stone blocks. The importance of porosity on rock fracture mechanism has already been found and works progress on the methods to measure the porosity. Other studies concern the improvement of computing methods relating to the behaviour of frozen soils while accounting for salt migration. The first step under progress is to create a system to measure the ice front displacement in such conditions that mechanical and thermodynamic parameters of equation can be determined. An experimental prototype cell has been built and tested with success. The principle is based on pressure measurements during an imposed constant liquid flow through the studied soils and measurement of the acoustic properties (Figure 2.).

![Graph showing speed of sound vs temperature](image)

Figure 2. - Sound speed in a humid soil versus temperature

3.2. Materials

One of the important questions concerning the materials to be used in cold regions is the risk of brittle fracture. Materials have a transition temperature below which they become brittle. For many materials, this transition temperature is not low enough to allow their use in structures to be operated in Arctic and Antarctic.

Another problem for such materials as concrete and plastic composites is aging when submitted to extreme conditions and to the large thermal cycles between summer
and winter. Four projects relating to these subjects are now in progress.

The first project deals with the definition of the service temperature of the materials. The State of the Art is to use the meteorological temperature for material design temperature. The primary reason for doing so is that when a site is analysed, the only available data are meteorological data. It is well known however that the temperature is a parameter largely influenced by the system of measurement and the ambient conditions. There is therefore little reason to believe that the material temperature equals the meteorological temperature. A study was started some years ago involving Bureau Veritas, TAAF, Ecole Nationale des Ponts et Chaussées (ENPC), CNRS, Laboratoire d’Aérothermique de Meudon, in view of studying the correlation existing between conventional meteorological temperature and steel element temperature.

In conditions of strong sun radiation (Figure 3.), the observations and measurements have shown great differences (up-to 40°C). The influence of such parameters as wind speed, sun radiation and temperature history have been analysed through statistical tools.
A procedure to analyse the air/steel temperature has been established and tested. The application to year-round measurement is now in progress.

Figure 3. - Metal plate and meteorological temperatures
—Steel --- Aluminium—-Rocks ... Air

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The determination of statistical representation of the temperature variations is presently under investigation, mainly the lowest temperature in view to apply a probabilistic approach to the selection of steel qualities.

As a complement to steel, analysis of the service temperature of plastic composite elements is planned for the coming year. Aging of the composite elements, i.e. the evolution of mechanical characteristics versus time of exposition to the Antarctic conditions is also being studied. This project involves TAAF and IFREMER.

In addition to studies on small samples, actual on-site verification of the behaviour of the glass fiber composite hull under ice impact was performed during the trip of the ship Tupperware/Vagabond 3 in North Canadian waters. Throughout the outgoing and return trips, the hull was precisely monitored by radiography and ultrasonics. Initial results indicate good resistance of the glass fiber composite material. Involved in this action are Bureau Veritas, Kurbiel Expéditions, Beneteau Shipyard, IFREMER, with the cooperation of the Ministère en charge de la Recherche.

These theoretical works are complemented by an industrial project with the participation of the SOLLAC GTS/TFK companies, Institut de Recherche de la Sidérurgie Française (IRSID), Alsthom - Chantiers de l'Atlantique, Bureau Veritas and the sponsorship of the Ministère en charge de la Recherche. The project aims to:

- define a steel particularly well adapted to Arctic regions applications, which is easy to weld,
- set up a standard for future application.

Figure 4. Concrete beams in Terre Adélie
Concerning the behaviour of concrete in Arctic conditions, four prestressed concrete beams were anchored in the sea near the coast at Dumont-d'Ursille Base, in Terre-Adélie, in order to be exposed to the action of the sea water and ice, as well as to very low temperatures and high winds occurring during Antarctic winter (Figure 4.)

These beams, the dimensions of which are 0.4 x 0.4 x 6 m were built by Bouygues. Two of them are made of ordinary concrete while the other two are of high strength concrete.

To be used as a reference, four similar beams were built and stored in Bouygues premises.

After a two-year staying in Terre-Adélie, the beams were brought back to France in May 1988. A program of tests has been defined by the Ecole des Mines d’Alès. These tests will also be carried out by the Ecole des Mines d’Alès with the assistance of Bouygues. A first visual inspection showed no particular alteration of the beams.

This experiment has been realized under the control of the Ministère en charge de la Recherche.

3.3. Ships

Two projects concern the design of ships for polar regions. One of them deals with the conception of a small ship for use as a logistic base for polar expeditions. The project is conducted by the Société Française de Construction Navale (SFCN) in France and Bureau Veritas, with the sponsorship of the Ministère de l’Industrie. The idea is to return to the principle of the Nansen’s Fram ship. This ship is not designed to offer resistance to ice when the pack-ice closes but rather to lift up and remain stable.

The objective of the other project concerns the definition of the hull shape for a large merchant ice-breaker. The project participants include Alsthom - Chantiers de l'Atlantique and the Laboratoire de Glaciologie et de Géophysique de l'Environnement (LGGE - CNRS). This project is sponsored by the Ministère en charge de la Recherche.

One of the major difficulties for any ship project is the definition of ice loads, as the existing methods are mainly
empirical and do not correlate well with measurements under actual conditions. For this reason, a basic research programme has been started with the cooperation of Laboratoire de Glaciologie et de Géophysique de l’Environnement (LGGE – CNRS), Institut Français du Pétrole (IFP) and Bureau Veritas under the sponsorship of Ministère en charge de la Recherche. This project includes theoretical studies to develop a model of the ice pressure resulting from impact with a structure and laboratory tests to quantify the equation parameters used in the equations and verify the influence of the ice confinement and the load velocity. The first step of the research led the programme to the use of fracture mechanics to represent the different steps of the ice crushing and calculate the interactive forces between the structure and the ice. The modelling of the crack initiation in the ice has been completed and now this work is being further developed to include the increase of ice cracks to ice fracture (Figure 5.).

\[ \sigma_1 - \sigma_3 \text{ (MPa)} \]

![Graph](image)

**Figure 5.** - Ice stress versus time and observation of the first crack for various strain rates

3.4. Offshore Platforms

Several concepts of offshore platforms have been developed in France. Three of them are briefly described hereafter, each one having been designed for specific environmental and operating conditions.
3.4.1. NEKTON 8000

NEKTON 8000 is a floating oil production system with a 12,000 T deck load capacity which can be operated in harsh environment, such as the North Sea, or in iceberg infested areas, such as offshore Newfoundland. This floating production system is designed to withstand a 30-meter high 100-year wave and growler or bergy bit impacts.

NEKTON 8000 has been developed by a French Association composed of Bouygues Offshore, Institut Français du Pétrole and Alstom-Ateliers et Chantiers de Bretagne

The vessel is comprised of:

- a semi-submersible hull made of prestressed concrete and composed of 6 columns connected at their lower part with 2 longitudinal pontoons and 2 transverse pontoons,
- an integrated steel deck housing the topsides facilities,
- a multiple flexible riser system which can be quickly disconnected and reconnected,
- a 12-line catenary mooring system which can also be quickly disconnected and reconnected,

Figure 6. NEKTON 8000 model tests in St Johns' Newfoundland

This project has been developed within the framework of cooperation with Comité d'Etudes Pétrolières et Marines (CEP&M).
The structure interaction calculations and model tests (waves, sea ice, growlers) have been performed in Canada with Canadian financial assistance. Figure 6. shows the ice model tests performed in the Institute for Marine Dynamics Ice Tank in St JOHNS. C-Core, CNRC and Memorial University of Newfoundland have also been involved in this development.

3.4.2. GRAVITY BASE PLATFORM "ZEE STAR 120"

The gravity base platform "ZEE STAR 120" is a mobile drilling unit intended for use in the Beaufort Sea in 42 to 120 foot deep waters (14 to 40 meters). Figure 7. gives an artist's view of the "ZEE STAR 120". This platform must especially withstand the action of a 7.5 m thick multiyear ice floe with 33 m thick ridges. It allows the drilling of 3 wells with 270 days' autonomy and is provided with accommodation for 90 people. The equipment is installed on 2 winterized decks integrated within the structure.

ZEE STAR 120 is composed of 3 parts:

- a prestressed concrete gravity base structure in the shape of a 12 side truncated pyramid, the internal structure of which is made of a high strength concrete 3-dimensional truss,
- a lower deck surrounded with a wave wall designed to withstand the pressure of the maximum wave and ice rubble loads,
- an upper deck mainly supporting the drilling equipment.

Figure 7. "ZEE STAR 120"
3.4.3. "LSP" DRILLING PRODUCTION PLATFORM

The LSP (ice-resistant platform) project intended for the TCHAIVO oil field, offshore SAKHALIN Island, in 30 m water depth, has been designed keeping in mind its adaptability to water depths up to 150 m. Figure 8. gives an artist's view of the "LSP".

This gravity base platform must specifically withstand the actions of 2 m thick annual ice floe with 14 m thick ridges. In addition, this area has no deep water sheltered site which would allow a deck mating according to the method used in the North Sea. These particular conditions governing the fabrication and the installation, in addition to the in-service conditions, have led to the development of a gravity base platform concept comprising:

1. a base with an internal structure made of a high-strength concrete 3-dimensional truss,
2. an integrated deck installed by self-elevation by means of DELONG jacks
3. a central column which ensures the protection of conductor pipes and supports the deck.

This central column is inserted between the base and the deck. The 3 parts are then fastened together after which the DELONG jacks and associated tubular legs are removed. This patented method allows the platform to leave the fabrication yard with a draft not greater than 12 meters.

FIGURE 8. "LSP" PLATFORM
4. CONCLUSION

DIPOL has permitted to show clearly how numerous and important the questions to be studied in the Arctic field are. Although many works and studies have been started and are now under progress, many gaps have yet to be filled. Important works have to be undertaken concerning in particular the knowledge of environment and its characterization as well as the means of calculation and the rules and standards to be applied.

For this purpose, DIPOL regroups different but complementary organisations and creates between them a synergy. Universities, Research Centers, Institutes, Laboratories, Engineering, Construction and Certification Organizations cooperate in a large and fructuous manner.

Although DIPOL is a French association, its technical vocation is international and the Franco-Canadian actions are a good illustration of this international cooperation.

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numerical methods for dynamic analysis of non linear mooring line forces under regular and irregular waves were developed.

3.6 Soil/Structure Interaction

The soil box facilities were employed for large scale modelling of stress-deformation state of offshore platform piles and gravity foundations under the action of static vertical and horizontal loads. Dry and water saturated sand were both used. Mathematical and numerical techniques were developed for spatial action and non-linear deformation versus load for piles and gravity foundations.

On the basis of the experimental study a physical model was proposed and a numerical method for vertical settling of offshore gravity platforms under cyclic wave loading was developed. The method explains why the settling of gravity structures on water saturated sands under horizontal cyclic loading can be an order of magnitude greater than settling under equivalent static horizontal loading.

3.7 Modelling of Ice Resistant Platforms

A complex large scale model study of different shaped, (cylindrical and cone-cylinder co-ordination), reinforced concrete ice resistant platforms was undertaken to determine the effect of simultaneous action of vertical and horizontal loads and low temperatures. Analogous studies of r-c elements, (beams, slabs, prisms, etc) were also undertaken. The models were up to 1.6m in diameter, 1.4m in height with a wall thickness of 0.05 to 0.10m. The research work resulted in the determination of the complex stress-deformation state of r-c shells and elements under combined action, structure crack resistance, and frost resistance with regard to concrete water saturation. Physical models of the studied phenomena were proposed and methods were developed for calculation of the stress-deformation state of r-c ice resistant platforms. Recommendations were also developed for the selection of concrete grade and reinforcement requirements to help increase the reliability of the structures.

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3.3 Wave Loading on Ice Resistant Platforms

In the wave basins, extensive research has been carried out on regular wave action on different shaped, (cylinder, cone, monopod, under-water cylinder etc), large cross section ice resistant platforms. On the basis of wave diffraction theory, calculation methods for wave loading on different structure types were developed, (in association with the Hydromechanics Institute of Academy of Science, Kiev). The calculation techniques were confirmed by experimental data. The calculations indicated that wave loads on specific platform types, (cone, for example), may exceed the load on that structure from an ice field, essentially if icing on the structure is prevented. This result confirms the necessity to optimise the shape of ice resistant platforms.

3.4 Scour and Scour Protection

For the first time, local bottom scour due to current and wave action around cylindrical and conical gravity structures was studied experimentally.

Methods for scour protection were also studied. Similarity and dimensional analysis techniques were combined with a generalised form of the experimental research results to help develop methods for local scour modelling and scour depth prediction. Additionally, techniques for evaluation of rock and gravel rip-rap characteristics to achieve scour protection around the structures were proposed.

The research results show that the relative local scour depth below natural seabed around large cross section cylindrical structures \((D/d = 1-4)\) at high and low tides is equal to \(H_b/D = 0.05-0.15\). This is an order of magnitude less than equivalent scour around bridge piers in rivers where \(D/d < 0.2\). (\(D = \) cylinder diameter, \(d = \) water depth, \(H_b = \) local bottom scour depth). Relative depth of local scour around cylindrical supports arising from wave action is commensurate with relative depth arising from currents.

3.5 Tanker Mooring Forces

Experiments with model tankers in the wave basin, field research in one of the Black Sea ports and the application of similarity and dimensional analysis, have resulted in the development of techniques for calculation of ship mooring forces at a berth due to wave action. In the wave basin, forces in mooring hawser at a single point mooring were studied and
3.1 Ice Loading

Physical and mechanical characteristics of flat and hummocked ice, and resultant loads on different shaped offshore structure supports, (cylindrical, conical, right angled), were studied on specially constructed large scale installations on the shelf of Sakhalin as well as in the ice basin of the Arctic and Antarctic Institute (Leningrad). The field research resulted in the development of techniques to define physical and mechanical ice characteristics by means of mechanical failure tests on small ice blocks and ice beams, and non destructive (acoustic) testing. A substantial amount of ice characteristic data has been accumulated in this way.

As a result of the experimental and physical research, techniques for calculation were determined for horizontal loading from a flat ice field on cylindrical supports of different diameters in the range $1 < D / h < 20$, where $D$ is support diameter and $h$ is ice field thickness. It was shown that when the ice field and support are frozen together (at $D/h > 10$) the ice load doubles.

Vertical loading on cylindrical supports from an ice field at low and high tide has also been investigated and calculation techniques developed. Similarly, calculation techniques for horizontal ice loading on conical supports were determined from the research work.

A field study was conducted on hummock parameters and resultant loading on cylindrical supports. The tests show that for hummocks of above water height 3 to 4 times ice field thickness, the loading on the supports increased 3 to 4 fold.

3.2 Wave Loading on Deep Water Jacket Structures

As a result of theoretical and experimental study of regular and irregular (random) two dimensional wave action on deep water jacket structures, numerical methods for evaluating dynamic behaviour have been developed taking finite wave height into account. On the basis of the numerical research, it was shown for the first time that statistical characteristics of dynamic structure reaction and response do not, in practice, depend on random wave spectrum type, but, in general, depend on correlation between velocity and inertial wave load components, flexibility of the structure and its length along the wave ray.
depth up to 1.0m), equipped with three movable shield wavemakers for production of regular waves.
- two short wave channels, both 1.4m deep, 1.2m x 26m and 1.7m x 29m, in plan, respectively, equipped with wavemakers for production of regular and irregular waves;
- large wave channel, 87m long, 2.5m deep and 1.7m wide, equipped with shield wavemakers for production of both regular and irregular waves;

2.2 Soil/Structure Interaction

For the study of soil interaction with structural piles and gravity based offshore structure foundations under combined horizontal and vertical loading, two soil test boxes are available:
- three sectional reinforced concrete (r-c) box, 5.8m x 7.6m with two glass walls;
- two sectional r-c box 16m x 6.5m with two sections 4m and 3m deep for work with water saturated soil.
The soils facility is equipped with a travelling crane and hydraulic cylinders for creating static and dynamic loading conditions.

2.3 Ice Studies

For the study of the stress-deformation state of ice resistant reinforced concrete offshore structures, and of r-c structural elements, under various load conditions, the following facilities are available:
- refrigerating chamber 12m³ in volume with hydraulic power plant;
- thermal pressure vacuum chamber TPV-800 8m³ in volume (made in GDR);
- thermal pressure vacuum chamber TPV-200 2m³ in volume (made in GDR);
- thermal chamber TC-800 with 0.8m³ capacity.
For the study of flat ice field and hummock interaction with different types of ice resistant structures a special ice basin, 7m x 3.5m x 1.0m is being constructed with refrigeration facilities.

3. OVERVIEW OF SELECTED RESEARCH PROJECTS

The main results of long term research on a number of important problems are given below.
comprises a two storey engineering building (1600m²), a one storey laboratory building (5000m²), and an ice basin compressor facility (500m²). The laboratory employs nearly 70 qualified scientists, engineers and other technical personnel.

The laboratory carries out complex research in two main directions on behalf of enterprises and research institutes of oil and gas industry ministries. These directions are:

- development and definition of the characteristics of environmental features (ice, waves, currents etc), and determination of the interaction of these environmental forces with offshore structures, and their effect on structures situated in both frozen and ice free waters;
- study of general stability and strength of different types of offshore structures, and development of appropriate analytical techniques.

The research work undertaken can involve both theoretical methods, (including numerical techniques), and physical modelling, both at laboratory and natural scale. Analytical techniques developed during the research work have been put into practice at several different project institutes for the prediction of the behaviour of offshore structures.

2. FACILITIES

The main installations available at the research centre are described below in the context of the different research areas undertaken.

2.1 Wave Behaviour and Loading

The wave facilities are used for a number of different research applications, including:

- study of wave action on different offshore structure configurations situated both in frozen and ice free seas;
- wave effect on installation of offshore structures;
- interaction of waves and ships;
- study of wave behaviour on port and harbour facilities;
- coastal wave behaviour.

The wave facilities available are:

- deep water concrete wave basin 45m in length, 12m wide with 2.5 and 4.5 variable depth. Basin is equipped with a shield wave maker for the production of regular waves;
- shallow water concrete wave basin, 28m square and 1.4m deep (water
THE MCEI LABORATORY AS A CENTRE OF OFFSHORE OIL
AND GAS PRODUCING STRUCTURES RESEARCH

V.A. Lobanov
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ABSTRACT

This paper describes the main features of the MCEI research laboratory. The activities of the laboratory in the area of research into oil and gas producing offshore structures are presented. Experimental facilities, installations and laboratory equipment are outlined, and some results of recent research, using the facilities, are given. The MCEI research centre provides a capability that is available for specialised testing and investigation work into the behaviour of offshore structures subject to environmental forces. This capability is enhanced by the extensive experience of the Soviet-British joint venture, Intershelf, formed between J P Kenny, the international subsea engineering specialists, and the Moscow Civil Engineering Institute together with the Industrial Construction Bank of the USSR. Intershelf is currently the only international joint venture operating in the Soviet Union with specific scope for the development of offshore projects.

1. INTRODUCTION

The oil and gas producing offshore structures (OS) laboratory was established by the Moscow Civil Engineering Institute (MCEI) in 1964. The laboratory, since formation, has become the largest centre of research into offshore oil and gas producing structures within the Public Education State Committee system. The modern laboratory complex covers an area of 10,000m² in Mytishi, not far from Moscow. The complex
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