Proceedings

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Additional POAC 85 Papers
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Post Conference Seminar
Ilulissat/Jakobshavn, September 14-18, 1985
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Preface</th>
<th>1065</th>
</tr>
</thead>
<tbody>
<tr>
<td>POAC International Committee - March 1986</td>
<td>1066</td>
</tr>
<tr>
<td>Permanent POAC Secretariat</td>
<td>1068</td>
</tr>
<tr>
<td>Revised list of POAC 85 participants</td>
<td>1069</td>
</tr>
<tr>
<td>Revised list of participants to the post-conference seminar in Jakobshavn/Illulissat</td>
<td>1084</td>
</tr>
</tbody>
</table>

## OPENING SESSION

- Opening Speech by Tom Høyem, Minister for Greenland 1091
- Opening Speech by Jonathan Motzfeldt, Premier, Greenland Home Rule 1102

## ADDITIONAL POAC 85 PAPERS

<table>
<thead>
<tr>
<th>AUTHOR(S)</th>
<th>TITLE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Schwarz, J.</td>
<td>PHYSICAL MODELLING TECHNIQUES FOR OFFSHORE STRUCTURES IN ICE</td>
<td>1113</td>
</tr>
<tr>
<td>Arikainen, A.</td>
<td>THE NORTHERN SEA ROUTE: ITS PAST, PRESENT AND FUTURE</td>
<td>1133</td>
</tr>
<tr>
<td>Carstens, T.</td>
<td>POLAR LOWS - A THREAT TO OFFSHORE OPERATIONS IN NORTHERN WATERS</td>
<td>1149</td>
</tr>
<tr>
<td>Goldstein, R.V. Osipenko, N.M.</td>
<td>SOME MECHANISMS OF LOCALIZED FRACTURE OF ICE COVER UNDER THE ACTION OF COMPRESSION</td>
<td>1170</td>
</tr>
<tr>
<td>Hoffmann, L.</td>
<td>IMPACT FORCES AND FRICTION COEFFICIENT ON THE FOREBODY OF THE GERMAN POLAR RESEARCH VESSEL 'POLARSTERN'</td>
<td>1189</td>
</tr>
<tr>
<td>Hoikkanen, J.</td>
<td>MEASUREMENTS AND ANALYSIS OF ICE FORCE AGAINST A CONICAL OFFSHORE STRUCTURE</td>
<td>1203</td>
</tr>
<tr>
<td>Author(s)</td>
<td>Title</td>
<td>Page</td>
</tr>
<tr>
<td>-----------------------------------</td>
<td>----------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>Bruun, P., Sackinger, W.M.</td>
<td>BRIEF PRESENTATION ON PORT AND COASTAL STRUCTURES IN ICE - SOME AMERICAN AND CANADIAN EXPERIENCES</td>
<td>1223</td>
</tr>
<tr>
<td>Buch, D.</td>
<td>12 YEARS PROGRAMME FOR BASELINE STUDIES IN JAMESON LAND, EAST GREENLAND</td>
<td>1241</td>
</tr>
<tr>
<td>Christensen, M.</td>
<td>DEVELOPMENT FOR THE FUTURE YEARS - GREENLAND</td>
<td>1243</td>
</tr>
<tr>
<td>Fabricius, J.</td>
<td>NORMAL AND EXTREME ICE AND NAVIGATION CONDITIONS IN DAVIS STRAIT AND DISKO BAY</td>
<td>1254</td>
</tr>
<tr>
<td>Hansen, J.C.</td>
<td>ACTUAL EXPOSURE TO HEAVY METALS IN GREENLAND, NATURAL AND MAN-MADE SOURCES</td>
<td>1261</td>
</tr>
<tr>
<td>Iversen, T.M.</td>
<td>GREENLAND TELECOM - TELECOMMUNICATION UNDER ARCTIC CONDITIONS</td>
<td>1279</td>
</tr>
<tr>
<td>Langager, H.C.</td>
<td>A PROPOSED HYDRO POWER SCHEME AT ILULISSAT, GREENLAND</td>
<td>1288</td>
</tr>
<tr>
<td>Reeh, N.</td>
<td>LONG CALVING WAVES</td>
<td>1310</td>
</tr>
<tr>
<td>Reeh, N.</td>
<td>ICE SHEET DYNAMIC MODELLING WITH ENGINEERING APPLICATIONS: A NON-STEADY STATE ICEFLOW MODEL FOR THE MARGINAL ZONE OF THE GREENLAND ICE SHEET</td>
<td>1328</td>
</tr>
<tr>
<td>Rosendahl, G.P.</td>
<td>ENERGY PLANNING IN GREENLAND</td>
<td>1330</td>
</tr>
<tr>
<td>Rosendahl, G.P.</td>
<td>TOWN PLANNING AND HOUSING IN GREENLAND</td>
<td>1339</td>
</tr>
<tr>
<td>Skærbo, O., Hulgaard, E. (p. 1359)</td>
<td>EXAMPLES OF HARBOURS AND HARBOUR CONSTRUCTIONS IN THE GREENLAND TOWNS AND SETTLEMENTS</td>
<td>1357</td>
</tr>
<tr>
<td>Olsen, C.P., (p. 1377)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steenfos, H.P. (p. 1421)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sprunk-Jansen, E.</td>
<td>CO-OPERATION BETWEEN MINING COMPANIES AND THE LOCAL SETTLEMENT - THE MAARMORILIK CASE</td>
<td>1422</td>
</tr>
<tr>
<td>Title</td>
<td>Page</td>
<td></td>
</tr>
<tr>
<td>--------------------------------------------</td>
<td>------</td>
<td></td>
</tr>
<tr>
<td>Sprunk-Jansen, E. THE ENVIRONMENT AND THE MINING - THE GREENEX CASE</td>
<td>1423</td>
<td></td>
</tr>
<tr>
<td>ERRATA</td>
<td>1463</td>
<td></td>
</tr>
<tr>
<td>SOUVENIRS</td>
<td>1465</td>
<td></td>
</tr>
</tbody>
</table>
The POAC 85 Organizing Committee are pleased to present the publication of the third volume of POAC 85 proceedings containing the official opening speeches of Minister for Greenland, Tom Høyem, and Premier of Greenland, Jonathan Motzfeldt, as an introduction to the papers not included in volumes 1 and 2 of the proceedings.

Besides, volume 3 contains the papers presented in Ilulissat/Jakobshavn at the seminar held especially on Greenland conditions.

The participants will surely agree with me that we all appreciated being so expertly informed about the many activities of the societies of the high Arctics. It was inspiring to learn about the challenge facing the people of Greenland to develop a modern, socially well-balanced society.

POAC wish to thank those we met for their hospitality which we shall never forget, as we shall always remember the magnificent nature of icebergs emerging from the glacier of the Icefjord.

I wish to thank all the lecturers and all who assisted us in making a success of POAC 85 in both Narssarssuaq and Ilulissat.

The coming POAC 87 Conference will be held in Alaska and will be organized by the University of Alaska, Fairbanks.

Per Tryde
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Ms. P. Sackinger
OPENING SESSION
Ladies and Gentlemen!

'The Man from Aluk' is the name of one of the oldest legends from Greenland - dealing with a hunter from the settlement of Aluk on the east coast of Greenland. He was very happy to live in his settlement and to watch the sunrise above the horizon every morning when he left his tent. His son, however, was an adventurer. Every year he would pester his father with requests that they leave for new settlements, but the father did not give in for a long time, until one day he was persuaded.

They travelled south and west, well, they may even have reached Narssarssuaq. The father longed for his home - for where they were, mountains and rocks would shade the sunrise. Calming down, the son gradually started realizing that his father was worth listening to - and they returned home to Aluk. The following morning the father left his tent to watch the sunrise over the horizon and was so deeply stirred that his heart burst.

Of course, the point of the myth is not only the relationship between the generations and the life of nomads in relation to the life of residents, but also
the progress of the human being in the process of life, in which the older to a greater extent is seeking his own basis.

When Greenland in 1953 ceased to be a Danish colony and became part of the Danish realm, one of the new constitutional requirements of the Danish constitution was that two members of the Danish Parliament should be elected in Greenland, and two on the Faroe Islands.

Mr. Augo Lynge was one of the first Greenland members of the Danish Parliament, and he was also a poet.

In a small poem he made the man from Aluk his subject in order to describe how impatient Greenland was to participate in the rapid modern development. The poem goes as follows - translated word for word:

'We are just as impatient as the man from Aluk to see what is rising above the horizon the east is growing light as water. The heart is beating and our hands are reaching for the light of summer.

So, young people, be prepared Join us. The sun beams are visible over the mountain peaks, the new-born day is calling you to work. Gain strength.

Some are still asleep, wake them, they have nearly overslept. Encourage the depressed and the insecure, give them hope. Let us be united.'
Development in Greenland has indeed been rapid.

For centuries, Inuits have been living in the arctic region. They have a highly developed hunter culture, their livelihood being based on nature's own resources, and always adjusted to the rugged arctic environment. House-building, umiaks, kayaks, and dog sledges are a few examples of the high technical level of their craftsmanship.

The first Norsemen came here to Narssarssuaq exactly 1000 years ago. They named the place Stokkanes and introduced European traditions, such as stone buildings. Today, we have examples of their skill in the large church ruins revealing their splendid building technique. It was not till the outbreak of the second World War, and the subsequent supply and defence agreement between Denmark and Greenland on the one side and the United States of America on the other, that modern technology reached Greenland.

Here on the vast plain - Narssarssuaq - the establishment of the American main base Bluie West One was started on 6th July 1941. The base was of decisive importance to the air support of Atlantic convoys from the United States to the European battle fields, and as an intermediate landing ground for American planes to Europe. During the war, more than 20,000 planes would touch down at Bluie West One.

The establishment of the large military base in Greenland brought with it military know-how of arctic technology, being used by the local communities in post-war years, and also in connection with increasing industrial activity in the Arctic.
Life in Greenland had so far been static, but was now replaced by our more dynamic modern life. When using the word 'static', I do not mean that the Inuit stayed in one place, on the contrary, they would travel from one hunting ground to another on this enormous island with its rugged nature.

Eight 500-year old mummies were found by Qilakitsoq in 1972. A unique find historically and resulting in the extremely exciting scientific co-operation between various branches of science. The Qilakitsoq-mummies revealed that Inuits have not changed their way of life for centuries - not till modern technology made their daily lives less dependent on nature.

Rapid population growth has been triggered off by the changing health standards. Living resources are no longer the sole contribution to Greenland economy. New industrial activities have had to be introduced. Early industrial activities in Greenland developed around townships on the west coast with accessible waters, where modern industrial plants were built for the processing of fish products.

During the same period, blocks of flats were built to meet the demand for modern sanitary installations - which would have been more costly in traditional scattered housing.

The old mining activity of cryolite production by Ivigtut has been replaced by modern technologically advanced mining based on know-how from abroad.

This very month, oil exploration has actually been started on the east coast of Greenland by Jameson Land. Completely modern technology with its fascinating per-
spectives must be kept in harmony with the vulnerable environment, and enable Greenlanders to continue their traditional way of life.

In the wake of modern development follows construction firms, public technical organizations, shipowners and research institutions undertaking technological tasks in the arctic region. POAC - Port and Ocean Engineering under Arctic Conditions - was set up to satisfy the demand for interdisciplinary exchange of know-how.

I am happy to be able to say that a Danish-Arctic Association of Engineers was established earlier this year on a national level and in co-operation with the Danish Association of Academic Engineers.

The first POAC Conference was held in Trondheim, Norway, in 1971. There have since been conferences every other year in Iceland, Alaska, New Foundland, Quebec and the last one in 1983 was held in Helsinki, Finland.

This year Denmark is host, and it is a natural thing for us to hold the conference in Greenland.

It has not been easy to arrange this conference - the largest ever in Greenland - with 150 participants from 15 nations. It has, however, been made possible because of fruitful co-operation between the parties involved - namely the Greenland Home Rule Authorities, The Ministry for Greenland including the Greenland Technical Organization, The Arctic Hotel Corporation, as well as constructive planning made by research workers from the Technical University of Denmark and the Danish Hydraulic Institute.

During my term of office, I have endeavoured to ac-
quaint myself with the technological and environmental conditions in the Arctic. In May of this year, I visited CRREL in Hanover, New Hampshire, and C-CORE, St. Johns, New Foundland, where major research within arctic technology is being undertaken. Knowledge of these subjects is extremely important - also to the Greenland communities that have undergone radical changes in living conditions over the past 30 years.

But the Arctic may be of even greater importance to the entire world in future. For many years, the saying in Europe and the United States went: 'Go west, young man' - and in all fairness, economic expansion will no doubt be found along the Pacific Rim or more specifically in California as gateway to the new industrial centres around the Pacific for some years to come. But in my opinion, the following saying would be more suitable for the nineties: 'North to the future'. The importance of snow and ice will become increasingly obvious globally. In future, the arctic and of course the antarctic regions will be moving into the centre of attention for reasons of security policy, environment and resources - not to mention the fact that the history of our world has been 'filed' - so to speak - in the ice cap behind us. Today's scientists are able to drill so deep into the ice that analyses can reveal weather conditions 300,000 years ago - year by year.

It is actually necessary to draw on our imagination to picture to ourselves the importance of the arctic region to mankind in future.

Also here, transportation is essential to all industrial activity. Construction works call for the conveying of heavy objects by ship. Consequently, more knowledge of the properties of sea-ice is a necessity.
Increasing insight into meteorological conditions is vital in connection with drift-ice, icing and wind stress.

Fluctuating and very low temperatures require a thorough knowledge of the properties of materials, and in connection with the building of harbours or other construction works it is all-important to know the physical and mechanical properties of ice.

Much is naturally also expected from the research into - and knowledge of - arctic technology in connection with local building and construction works etc., well, with the building up of a normal infrastructure in arctic regions in general. It is this very infrastructure which could be the most fascinating in future. The contrast between centralization and decentralization is being discussed in many parts of the world - as is also the contrast between traditional life and modern technology.

But although paradoxical, it is still a fact that without centralization no decentralization, without the most modern technology no traditional life. And this exactly is our challenge.

The exploitation of hydro-electric resources for local as well as industrial use calls for expertise within arctic hydrology, glaciology, climatology, sedimentation, turbine technology etc. Oil exploration and possible later production require a wide knowledge within the above fields as well as within petrochemistry.

Suitable maps are a must when carrying out prospecting or construction activities, and the performance of
these tasks often requires a familiarity with geodetic and photogrametic methods.

Communication and navigation services, meteorological and ice observation services, environmental protection, efficient rescue service etc. are even more vital in arctic regions to safeguard people, materials and the environment, than is the case under more southern skies.

Distances and the forces of nature are immense.

Greenland weather conditions may fluctuate from warm and bright sunshine to gales and icy cold weather, gusts of wind of around 180 knots have been observed here. Greenland does indeed represent a challenge to human know-how.

Great variations in climatic conditions are constantly calling for adjustments, such as the considerably milder climate during the middle of this century. Lately, from 1981 to 1984 winters have been extremely cold in south Greenland with temperatures 10 degrees centigrade below the average measured over the past 30 years.

This shows the need of climatic conditions requiring a change of standards for insulation, water supply, heating and sanitary installations, indeed for building and construction in general, as well as for ice, navigation and meteorological services. All these subjects will be discussed during this conference.

In my opinion, it is of decisive importance that all nations involved in arctic technology may find a forum here for the exchange of know-how, and that new common
research projects, if any, may be discussed in an effort to find ways of co-operating fruitfully in spite of different political observations and across borders.

Denmark feels obliged to act as a link between the European and North American commitments - also because of our geographical position.

In order to strengthen our commitment - to increase our arctic consciousness - I have set up a working group, which will shortly put forward a proposal for the establishment of a Polar Institute in Denmark.

My intentions are not that this institute shall take over all current Danish arctic research institutions, thus being able to head Danish arctic research.

It would be expedient to establish a library already in the introductory phase with a collection of arctic research literature, and a database with information about Danish and international arctic research.

Firms in Denmark and Greenland must be just as technologically advanced as foreign firms in order to participate on equal terms in the industrial development in arctic regions - and in this case, I am especially referring to Greenland.

But our small country - with its more than 250 years of arctic experience - should also have a fair chance of influencing the development in other arctic regions of the world. By way of example, 23% of the gigantic Chinese continent are areas with perma-frost. No wonder Danish firms see export of our arctic know-how within the range of possibility.
But to concentrate research work within the fields of technology and natural science would be a mistake.

In my paper, I have discussed issues relating to natural science and technology - as these issues will be of main interest here in Narssarsuq.

I am pleased to see - being a humanist - that the technocrats do not focus on physical problems only, thus overlooking an equally important aspect - namely the correlation between man and technology. However, this very issue will be the main theme of the subsequent seminar in Jakobshavn.

The man from Aluk was right in following his adventurous and enterprising son, as was the young man equally wise when listening to his older and more experienced father.

It is not just a set phrase that the scenery in Greenland is breath-taking, and that it makes you feel so small. Nature may be an impressive sight - but it is indeed just as impressive that man is able to adapt to his surroundings and even to make a living, however hard he may find it.

The Danish Permanent Secretary Mr. Eske Brun was without doubt the Danish official who has had the greatest influence on modern development in Greenland. He was active from 1934 to 1964 and experienced the replacement of the old ways of life by new and modern ones.

In his memoirs 'My Life in Greenland', he mentions a type of Dane that he could not stand being in the same room with, and says: 'Later on, I always felt bad when well-meaning people asked me whether Greenland was able
to cope with the rapid development, and were Greenlanders not much happier in former times - that is - if they asked me at all and not just expressed a fact'.

I want to make his words mine, for development in Greenland means houses, hospitals, jobs, harbours, airports and improved means of communication.

In Søndre Strømfjord, we might transmit radar pulses via the moon to Kiruna in the northern part of Sweden, enabling us to measure the actual movement of Greenland away from Europe towards the American continent - however, only with the speed of a growing fingernail. So it will take some time.

From a technological point of view, Greenland is, however, moving at a constantly increasing and indeed rapid pace.

Technology is not an enemy of mankind. On the contrary. The assertion that there are limits to growth is outdated. It is crucial that we set the pace ourselves - our souls must be given a chance to keep up.

It is my hope that this POAC conference of 1985 will be of benefit to everybody, and I hereby declare the Conference open.

Tom Høyem
Ladies and gentlemen!

Welcome to Greenland and welcome to Narsarsuaq to the opening of the 8th International conference on Port and Ocean Engineering under Arctic Conditions.

It is with great pleasure and it is a privilege for me to participate in the opening of this conference which is to take place for the first time in a part of the Arctic area where the indigenous people - the Inuits - form a majority compared to the people coming from the South.

Following the contribution of the Minister for Greenland, Mr. Tom Høyem, I should like to tell you about our home rule, which I have chaired for the last six years. It is my hope that it will be of interest to you to get an impression of how we in Greenland look upon our own present situation.

First of all, I would like to give you a short overview of the latest historical background, which led to home rule.

Until 1953 Greenland was a Danish colony. People lived in decentralized hunting communities - governed by the central authorities of Denmark. Greenland was a closed country, and in actual fact it was governed by the Royal Greenland Trade Department, which exercised complete monopoly of all supplies, trade, and traffic to or from Greenland - as well as within Greenland.

In 1953 - consequent to an amendment of the Danish constitution - Greenland formally became an integral part of the Danish realm with equal rights, and it was decided to open up the country, so that it might develop into a modern society, based mainly on fishing as an important alternative to traditional hunting.
Greenland became entitled to send two representatives to the Danish Parliament, while the nationally elected assembly: The Provincial Council - remained only as an advisory body to the Danish authorities.

Then followed two decades of violent change and transformation. During the fifties and sixties the Greenland society was completely changed. Factories were built in a number of selected towns on the Greenland West coast, and a great number of settlements were closed in order to concentrate the population in these towns. The Greenland hunter was to become a wage-earner and a consumer in a modernized and industrialized Greenland.

We young people of Greenland were to be educated in new schools with Danish teachers, who should not teach us Greenlandic - our mother tongue - but Danish. This step was considered necessary to enable the Greenlanders to survive.

The country also got new hospitals, in order to defeat the widespread tuberculosis, and new homes and blocks of flats were built to house the many new residents of the towns.

At the beginning of the seventies, many of these frustrations were put into words. Young Greenlanders - and I myself was one of them - formulated a claim for Greenland to be governed on Greenland's own conditions. We claimed influence, and we plainly stated that the equality obtained through the 1953-amendment could amount to cultural extinction, because it called for us: - the Greenlanders - to become Danes.

A few young politicians - who expressed these views - were elected in 1971 and 1972 to the Greenland Provincial Council and the Danish Parliament - the Folketing - respectively. The criticism of the Danish policy had been politically authorized, and it soon resulted in a claim for increased local autonomy.
Home rule was introduced on May the first, 1979 - six years ago. It consists of a parliament: - the Landsting - and a government: - the Landsstyre.

Maybe one of the most important features in the home rule system is the presence of political parties. Our party-system after a European-Scandinavian model was introduced in Greenland in the mid-seventies as a necessary condition for a parliamentarian system. Over the past decade, this system has developed so fast, that we today have a living democracy, that has the will and capability to deal with our country's problems. The parliament consists of three parties: - Siumut with 11 seats - Atassut also with 11 seats - and Inuit Ataqatigiit with 3 seats - a total of 25 members representing all parts of Greenland. Siumut and Inuit Ataqatigiit form a 7-member-government since June 1984.

The substance of the home rule is the transfer of jurisdictional powers from Danish authorities to the Home Rule Parliament and Government within certain areas of regulation, and confined to the Greenlandic territory. This means that the Danish parliament is no longer competent to enact legislation in Greenland within the areas of jurisdiction transferred to home rule.

During the first six years the home rule has taken over responsibility for many public areas - just to mention some: education and culture, social welfare, production and export. Within the next decade, the home rule will take over the rest of the public area that - according to the constitution and the home rule act - can be taken over.

Some areas of regulation cannot, however, be transferred to home rule authorities. Those are: defense matters, foreign policy matters, monetary matters, and judicial powers, which remain exclusive Danish powers.
However, this does not mean that we in Greenland do not have an opinion on these matters. As far as foreign policy is concerned, we negotiate and do in fact conclude international treaties with third countries in a few cases, such as: agreements with our neighbours on fishing management in the North Atlantic. In matters of defence, we naturally watch the global development, and questions of defense policy are frequently debated in our parliament. In such debates the existence of US-defense areas in Greenland often call for special interest - but also questions like nuclear-free zones are of current interest. In such matters the parliament passes - very often unanimously - advisory statements to the Danish government.

Normally, the taking over of a field of jurisdiction from the Danish parliament also implies assumption of the financial responsibility for that area. The home rule’s revenues derive from: taxation: about 65 million dollars, lump sum grants from Denmark: about 60 million dollars, and from EEC fishery-licences: about 20 million dollars.

These revenues are each year partly transferred to the regional municipalities - of which we have 18. This administrative structure was introduced in the early fifties, and is still maintained under home rule as a means of decentralizing the powers transferred to home rule authorities. A number of administrative functions regarding: education, social welfare, land-planning, etc., lie with these municipal authorities - and some limited regulatory powers are delegated from the home rule to the municipal councils in these areas. Settlement councils, however, have only advisory functions.

All this has in a way formed the basis for the creation of the Greenland we want. In the coming years we shall be taking over (from the Danish government) some very large areas of responsibility - that is: the transportation and supply of goods and technical activities.
In Greenland we have to be realistic about our possibilities of gaining more self autonomy over our affairs. So realistic, that we have to say to ourselves that without an increased degree of economic selfsufficiency or even independency of Denmark we can have no real hopes for an increased political autonomy in relation to Denmark or other nations for that matter.

Besides fishery, Greenland's possibilities of economic development lies in the field of mineral and oil resources. And we are forced to look for other sources of income and industrial activities to supplement and consolidate the present fishing sector which is very vulnerable to variations in biological and physical factors such as the size of the fish stocks, which again is dependent on the trends in the water temperatures and the prevailing ice conditions on the banks off Greenland, where the fishing actually takes place.

This is the background for the very broad support in Greenland as well as in Denmark to the granting of the first concession in the last 10 years with exclusive rights to explore and possibly exploit the oil that may be under the surface of Jameson Land, which is a 10,000 square kilometres land area in East Greenland.

The concession was granted to a consortium led by a Danish subsidiary of ARCO - a company with vast Arctic expertise from its operations at the North Slope of Alaska.

Over the coming months the Danish and Greenlandic authorities will start considering the initiation of oil exploration in other areas, which may have an oil potential - yet of unknown size.
We shall be doing this with the aim to obtain a steady level of activities and a continuity in operations where there will be different groups of oil companies operating in different areas with different kinds of activities, that is: seismic investigations, exploratory drilling, and hopefully also production in some years from now.

This should be in the interest of all parties involved: the oil companies, the governmental regulatory bodies, the manufacturers of equipment, and the scientific world because there will be an ever existing need for research and development of new technology to meet the requirements of the harsh climate, and the proper protection of the fragile Arctic environment.

As I stated before: we are in need of the income that the oil and mineral extractions can give us - but we do not intend to start exploitation at any price. Partly, because the vulnerable Arctic nature must not be damaged, and partly, because our cultural traditions shall not be overturned by an "oil adventure". Things must be balanced off against each other.

The accelerating development in this area also means: that the political structure between Denmark and Greenland - according to this specific area - must undergo some changes in the near future.

The present legal background is part of the Home Rule Act. According to this act, the "resident population has fundamental rights" to Greenland's non-renewable resources.

The legal character of these rights was never specified in the joint Greenlandic-Danish Home Rule Commission - because agreement could not be reached on this issue.
It was important, however, that at least some rights - of whatever substance - were recognized as a political declaration of principle for the Greenlandic population. Nor was the concept: "Greenland's resident population" ever specified, because there are no individual rights or privileges attached to this concept. It includes every resident citizen in Greenland - native or non-native - and the tasks following from the recognition of "fundamental rights" are carried out by the home rule on behalf of the population living in Greenland at any time, and to the collective benefit of these people. "Fundamental rights" are collective rights, separated and distinct from individual private rights.

The collective character of the Greenlander's "fundamental rights" to Greenland's natural/mineral resources is closely connected with the fact that private proprietary rights to land-surface or subsurface-values do not exist in Greenland, and have never existed.

In the absence of any clear definition of the "fundamental rights", the Home Rule Act instead contains: a practical provision, stipulating the procedure to be followed, whenever decisions on mineral exploitation are to be taken. According to this provision, agreement has to be reached between the Danish and the Greenlandic governments on every such decision. If agreement is reached, the Danish minister for Greenland affairs will issue the concession - for exploration or exploitation of the resource in question - to the applicant. If agreement cannot be reached, No concession will be issued! Thus, each of the two governments has the right to veto any decision regarding industrial use of Greenland's non-renewable resources. The details in this "raw materials arrangement" are spelled out in the complementary Mining Act for Greenland. In this mining act, a joint Greenlandic-Danish advisory council is established with five Greenlandic members and five Danish, and a chairman appointed by the Queen. This council is the body, where agreement as mentioned above has to be reached. I have the honour of being chairman of the council.
As for the allocation of revenues from the exploitation of mineral resources: the underlying principle is one of revenue-sharing. However, the mining act specifies, that the Danish state will receive compensation for the total annual expenditures on Greenland in advance, before any allocation is made.

Public revenues in excess of this compensation will then be allocated to the two parties according to a formula, which has not yet been decided upon. It may seem doubtful - whether public revenues from mineral activities in Greenland will ever exceed Danish total expenditures on Greenland, and this system of allocating the revenues has been much criticized in Greenland.

For this reason we will initiate new negotiations with the Danish government concerning a reformulation of the revenue-sharing.

Finally: I would like to say, that one of the important experiences from Greenland's Home Rule is the significance of holding jurisdictional/legislative powers at the highest possible political level, when providing for native self-government. If self-government means anything: it includes the power to decide by oneself the law of the land - and even the right to make mistakes when doing so. Self-government with only advisory or consultative functions against federal or state authorities will never satisfy the need of a native population for decisive influence on, and control over, matters which affect its interests.
Ownership and title-to-land is another important element in the development towards self-government, but it is not sufficient. It may provide: a legal protection against industrial abuse of the land-areas and violation of traditional native rights and wildlife management, but it cannot reach beyond that. General legislative powers have to be added in order to realize self-government. That is our experience - and it has been a pleasure to have been given the opportunity to express some Greenlandic viewpoints here today.

I hope, I have been able to enlighten the audience a bit more about what is actually going on here in Greenland, and I should like to express the same hope as Mr. Tom Høym just did: that the POAC-conference of 1985 will be of benefit to everybody.

However, I do hope, also, that the participants of the conference will make use of the possibilities to gain their own personal experience from visiting this part of South Greenland and - for those who participate in the post-seminar in Ilulissat/Jakobshavn: the Disko Bay Area too.

Thank you - and once again:

Welcome to Greenland!
ADDITIONAL POAC 85 PAPERS
PHYSICAL MODELLING TECHNIQUES FOR OFFSHORE STRUCTURES IN ICE

1. INTRODUCTION

While activities in the Arctic offshore regions are turning more and more from exploration to production, many new problems are evolving which need to be solved. Level ice and ridges are not any more the main concern, instead multiyear floes and icebergs must be considered to be the most critical ice conditions when designing production platforms, loading facilities, pipe-laying and dredging equipment and transportation systems. In order to be on the safe side, this equipment can be built overly strong. This, however, would be so expensive that Arctic oil or gas production would not be able to compete with resources from conventional offshore regions. To paraphrase the words of Sohio's Mr. Herrera at the OMAE Conference in Dallas earlier this year, what we need are innovative, economical offshore structures.

In the development of new concepts for Arctic offshore structures or transportation systems ice model testing plays a key role. Besides first demonstrations of the feasibility of new concepts, model tests are generally used to improve ideas, to study the interaction between structure and ice, to predict the ultimate ice loads, and to verify theoretical predictions of ice forces, for example.

Of course, model tests only make sense if ice conditions can be simulated and test results can be extrapolated to full scale with a high degree of accuracy.
For icebreakers this accuracy has been checked in many cases and was found to be quite satisfactory, at least for level ice. For offshore structures this feedback from full scale is scarcely available. Therefore, every occasion must be used to get full scale data on ice structure interaction.

2. SIMILARITY

So far, model testing in ice has been based on the requirement that Froude's and Cauchy's model laws are fulfilled. This means that the Froude Number

\[ F_N = \frac{v}{\sqrt{L \cdot g}} \]

and

the Cauchy Number

\[ C_N = \frac{\rho \cdot v^2}{E} \]

are equal in model and full scale.

\((v = \text{velocity}; L = \text{length}, g = \text{gravitation acceleration}, E = \text{elastic modulus of ice and } \rho = \text{density})\)

It has also been accepted widely that viscous forces (Reynold's Number) can be neglected because under normal test conditions they are much smaller than gravity, inertial (Froude) and ice-breaking forces (Cauchy).

Ten years ago, Atkins /1/ introduced the so-called Ice Number which takes into account the fracture toughness by the stress intensity factor, \( K \). Timco /9/ has presented results on the fracture toughness of sea ice and urea doped model ice. It appears that the fracture toughness of urea doped model ice is higher than in full scale sea ice, especially in the low range of strength. However, the question of how important it is to satisfy Atkins's model law in addition to Cauchy's law is
uncertain. Much more research is needed to decide on this issue.
A basis for this research is provided by guidelines for the performance of fracture toughness tests (IAHR Recommendations 1984 /6/).

A significant parameter in ice model testing is the friction coefficient between ice and model structure and between ice and ice. So far, it was assumed that the friction coefficient is independent of normal stress and velocity (Coulomb's friction) which allowed the friction to be equal in model and full scale.

Recently performed measurements on normal and tangential forces at the bow of the icebreaker, POLARSTERN, (Hoffmann, /5/) show that the friction coefficient strongly increases with decreasing normal force below a certain force level. A similar result has been found by Forland and Tatinclaux /3/ in friction tests (ice moving on plane plate) in the laboratory. Forland and Tatinclaux also obtained a distinct dependency of the friction coefficient on the velocity and the hardness of the ice. All results indicate that correct simulation of the friction effect in ice model tests is more difficult than currently assumed. The first step was the standardization of the testing method for establishing the friction coefficient, because in the past, each ice laboratory used its own method to carry out the friction tests.

Along with the problem of simulating the friction coefficient correctly there is also the difficulty of considering the effect of snow on top of the ice cover. To a certain extent, this effect can be taken care of by a higher friction coefficient. Russian publications, however, report on an increased resistance with increasing thickness of the snow layer. Here, experience and results from full scale tests are necessary to correct the model test result for the snow cover effect or to establish an equivalent ice thickness in order to account for the snow cover thickness.
If broken ice, perhaps mush ice, is to be simulated in model tests we have to consider that the internal shear stress between the broken ice pieces is highly rate dependent and that mush ice is a compressible fluid (non-Newtonian) (Hellmann /4/), for which the scaling laws are not yet established. Nevertheless, icebreaker model tests in mush ice have shown that the icebreaker performance was qualitatively similar to that which was observed in full scale (adhesion of mush ice clusters along the bow of the icebreaker at low speed).

According to the currently used model laws (Froude's and Cauchy's), the relationship between model and full scale values is governed by the following scaling functions:

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<td>Velocity</td>
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m = model scale; FS = full scale; λ = scaling factor
3. MODEL ICE

No model ice is perfect up to now, i.e., no model ice simulates the physical properties of sea ice correctly in every respect or to full satisfaction. The problem starts, however, with the question of which kind of sea ice is to be simulated: isotropic ice (snow ice, multiyear ice floes, or icebergs) or unisotropic level ice with its subsequent kinds of appearances.

Since the unisotropic columnar grained sea ice is predominantly found in the Arctic and model investigations have concentrated in the past on the simulation of structures and ships in first year level ice, it was this type of ice that most ice laboratories strived to reproduce. The advantage of level ice is the sufficient amount of available full scale data on its physical properties.

In the early stages of ice model testing (60s and early 70s) sodium chloride was widely used to reduce the mechanical properties with the disadvantage that the ratio of the elastic modulus to the strength ran out of range when the scale factor was larger than 10. This shortcoming was improved by the introduction of carbamide as dopant.

Today, most ice laboratories use carbamide model ice, for which the ratio of the elastic modulus to the flexural strength is larger than 1000, in most cases larger than 2000, and thereby in the lower range of sea ice values. The surface layer with its randomly oriented crystal structure is equivalent to the surface layer of sea ice. Reported separation of the surface layer from the columnar part of the ice can be avoided by correct fabrication methods. The ratio between compressive (load applied vertical to long axis of columns) and flexural strength is 2 to 3 and therefore also close to that found in nature.
In model tests with the icebreaker, POLARSTERN, the breaking pattern and the floe size of the carbamide model ice was found to be realistic, i.e. similar to what was observed in full scale (Fig. 2).

The disadvantages of the carbamide model ice are:
(1) the complex fabrication process,
(2) the time and energy consuming process of tempering the ice before testing for achieving the required properties and
(3) the as yet not correctly scaled elasticity or fracture toughness (s. Fig. 1) which effects the results, especially in the low velocity range.

Due to the progress of Arctic offshore research and the development from exploration to production, the ice conditions to be considered have to include besides first year level ice and pressure ridges, also multiyear ice floes and multiyear ridges, which predominantly consist of isotropic granular ice with low salinity content.

A fine-grained micro-structure model ice which simulates the isotropic properties was developed by WARC (Wärtsilä Arctic Research Center) (Enkvist and Mäkinen /2/). It is reported that this ice breaks in a brittle manner and provides a breaking pattern of the ice more realistically than saline columnar-grained model ice. One major drawback of this fine-grained model ice is that the ratio between compressive and flexural strength is reported to be only in the range of 1, while in natural sea ice, as well as in carbamide model ice, it is between 2 and 3. This means that if both ice failure modes are involved in the ice-structure/ice-ship interaction, micro-structure ice is also not yet the proper modelling material.
Synthetic ice has the disadvantage of being sticky. This leads to unrealistically high friction coefficients, especially between ice and ice. Since friction has a dominant effect in ice-structure and ice-ship interactions, tests in which this synthetic ice is used are not considered to produce reasonable results.

4. ICE CONDITIONS

In the early stages of ice model testing (up to 1978), icebreaker and offshore structure models were tested in level ice only. Nature, however, provides besides level ice, many other ice features such as brash ice, mush ice, pack ice, rafted ice, rubble ice, pressure ridges, and the multiyear ice floes, icebergs and ridges. Several of these ice features are much more dangerous for offshore structures than just level ice. Therefore, it is quite obvious that ice model basins need to develop techniques to simulate, at least, some of these higher force producing ice features.

The real problem here is the lack of full scale information, for example, on the properties of pressure ridges, of rafted ice or of rubble ice. The reason for this lack of information are the difficulties involved in measuring these properties in full scale.

For pressure ridges we know statistical values of the geometry and the degree of consolidation; also some index strength data obtained by Bore Hole Jack tests are available. Based on this information, pressure ridges are being simulated by various methods. At the Hamburg Ship Model Basin (HSVA) the geometry is simulated by a cast which is filled with prebroken ice pieces. The top layer is refrozen and the degree of consolidation is controlled by placing blankets on the ridges for definite
periods of time during the refreezing process. The underwater ridge geometry is monitored by a sonar device (Mesotech). Additional efforts are still necessary in order to gain more confidence in the simulation of ridges in model tests.

One way of bypassing the problem of correct simulation of ridge properties in model tests is the idealization of ridge geometry and mechanical properties by using a strip of solid ice. For this well defined condition the interaction forces with a certain offshore structure are calculated theoretically and compared with the measurement from the model test.

Brash, rubble and mush ice can also be simulated in model tests. Governing parameters are the piece size and the internal shear angle. The latter is obtained through shear box tests and varies, according to Hellmann /4/, between 35° and 70° depending on the velocity of the shearing process. The extremely high shear angle occurs at very low speeds.

Rafted ice has been simulated in model tests at HSVA for given strength properties in order to check theoretical calculations. The strength properties were controlled and measured like in the case of level ice. No information seems to be available on the important question of how strong the various layers are bonded together.

Multiyear ridges and multiyear ice floes have been simulated in model tests by idealization of the geometry. Multiyear floes have been produced in the model tank by seeding micro-structure ice, whereby the isotropic crystal structure is simulated and the strength is scaled.
5. **EXAMPLES OF MODELLING ICE/STRUCTURE INTERACTION**

5.1 Introduction

When in the late 60s and early 70s model testing in ice spread out from the Soviet Union to Finland, West Germany, the USA, Canada and Japan, the most common test with icebreaker models was the resistance test in level ice. Today, icebreaker models are more and more being tested in the self-propulsion mode and make up about 50% of the work load of ice model basins. The other 50% deal with offshore structures in ice for which we distinguish between fixed structures and floating moored structures.

While in icebreaker operations mean values of resistance and propeller thrust and torque are of importance, the survival of offshore structures depends on the ultimate ice forces exerted by the most critical ice condition existing in the area in which the structure is intended to operate.

5.2 Tests for Fixed Structures

The simplest test subject is the fixed vertical cylinder for which in most cases only the horizontal force and speed are measured. The data analysis, however, should include probability and spectrum analyses in order to provide information on the probability distribution of the forces and on possible effects of the natural frequency of the experimental set-up on the force result.

In the case of vertical piles penetrating level ice at a certain speed, crushing failure prevails. An example is shown in Fig. 3, where a 5 cm thick level ice cover is being penetrated by a 100 cm wide circular column. At this d/h ratio of 20, crushing changes to buckling or bending when the speed is decreasing.
Relatively uncomplicated are model tests on fixed cones in level ice. In this case, forces are measured in x, y and z directions. By suitable arrangement of the force transducers also the point of force application can be determined.

Recently, the interaction of multiyear ridges and multiyear ice floes with fixed cones have been tested at HSVA, in which, besides the forces, the kinematics of the ice was investigated and compared with theoretical models.

Modelling multilegged structures in ice requires special care that forces are not transmitted from one leg to the other if the stiffness of the entire structure is not simulated and that the model ice is brittle enough as to provide broken ice pieces of correctly scaled size in order to simulate the ice clearing behaviour between the legs (s. Fig. 4). (Especially this clearing cannot be simulated by sticky synthetic ice or the too plastic saline ice.) The analysis of these tests provides forces in all three directions (x, y and z) on each leg and also on the entire structure.

If an infinite level ice cover or rafted ice or ridge is to be simulated, the ice in the presently available size of ice model basins (max. width 10 m) should remain fixed to the sidewall during the test and the structure should be pushed by the towing carriage through the ice. HSVA uses for such tests an underwater carriage as a support for these structures.

If tests for offshore structures are carried out by pushing the ice cover and keeping the structure in place, in most cases, the ice does not fail in a similar manner to full scale due to the possibility of crack propagation toward the ice edge along the sidewalls of the tank. In some cases this finite stress state reduces the forces (for example, the crushing forces of vertical pile indentation) or the forces are higher than in reality (for example, when a conical structure breaks level ice into unreal-
istically large ice floes, the clearing of which induces higher forces).

5.3 Tests for Floating Structures

The most challenging model test program HSVA has performed so far, were the tests for Gulf Canada's Conical Drilling Unit (CDU) which is being operated successfully in the Beaufort Sea for exploration under the name "Kulluk". The CDU is a floating circular polygon consisting of 24 sides (Fig. 5). It was designed to break ice by way of its downward breaking conical shape. It is moored by 12 mooring cables. These cables were simulated by wire ropes and springs which were selected as to reproduce the required spring constants. In order to simulate the entire dynamic behaviour of the CDU, not only the mooring system but also the full scale dynamic trim conditions were simulated. A certain preload was applied to all 12 mooring cables. Measured items were the 12 mooring cable forces, the motions in x, y and z directions, pitch, roll and yaw.

A computer program was established by which the system forces in all three directions were calculated on the basis of measured mooring cable forces, displacements and rotations. These system forces were compared, for example, with the system forces in x direction calculated by multiplication of the measured surge by the system spring constant in the x-direction. The agreement between both system forces was excellent in the operational range of the Kulluk.

In the course of the model tests, the underwater shape of the CDU was modified in order to avoid ice ingestion into the mooring lines under normal operating conditions. The tests were carried out in level ice and in level ice with ridges having different degrees of consolidation. In addition, special ice managing tests were performed to establish the towing forces through various ice conditions in order to develop procedures
for towing the CDU most efficiently.

5.4 Tests for Oil Transloading Systems

As the offshore activities in the Arctic turn to production, oil and gas terminals, oil transloading systems are being developed as well. Single buoy or tower moored barge systems have been tested at HSVA for several customers. All these systems have in common that a storage tanker is anchored on a tower or buoy and is allowed to weathervane according to wind, sea and ice conditions. The articulated tower may be fixed to the bottom by a universal joint and kept in the more or less upright position by buoyancy and mooring lines. This positioning job can also be handled by a buoy which is anchored to the bottom by mooring cables. Experience with those systems is available in open water, but can these systems also be used under ice conditions?

Questions have to be answered such as:

(1) How big are the ice forces against the side wall of the tanker, if the tanker at the beginning of the ice motion is not in line with the drift direction of the ice but perhaps perpendicular to it?

(2) What are the forces in the connections (yoke) between turret and tanker?

(3) What are the forces in the mooring lines and in the joint at the bottom of the tower?

(4) What are the ice forces against the tower or buoy without tanker?

(5) What are the motions of the tanker or the barge for all these operational conditions?
In order to answer these questions, model tests have been carried out (s. Fig. 6) and theoretical models have been developed. Most of the results are presently still proprietary, but one paper will be published at the OMAE 86 Conference by Norimatsu, Minami and Schwarz /7/ in which a prediction method and model test results are presented.

Tower moored barge systems are probably only suitable for moderate ice conditions, i.e. first year ice floes, level ice and ridges up to a limited thickness.

6. HSVA'S NEW ICE MODEL BASIN

All the model tests mentioned so far which have been carried out at HSVA have been performed in a second generation ice tank which is 30 m long, 6 m wide and 1.2 m deep. Since the beginning of this year, HSVA is also operating a new ice model basin which has a total length of 78 m and a test length of 60 m, is 10 m wide and 2.5 m deep (s. Figs. 7 and 8). The new ice tank also has a deep water section of 10 m x 10 m which is 5 m deep. This will be used for offshore structure investigation in which, for example, mooring problems in deeper waters need to be simulated. Storage tanks are situated below the ice model basin for storing the water while the models are being installed on the underwater carriage. Along the centerline of the tank bottom are windows for observing and recording on video, photo or 16 mm film the ice-ship or ice structure interaction from below. The visual documentation of the icebreaking and ice clearing processes is carried out also by video cameras mounted to an underwater carriage.

The main towing carriage weighs 50 tons. It develops a thrust of up to 50 kN within a speed range of 1 mm/s to 300 mm/s in the longitudinal direction. The data sampling and processing computers as well as the speed control system are housed in heated
chambers on the towing carriage.

Another self-driven carriage of high stiffness is used for ice property measurements before and after the tests as an observation platform during the tests and for any support necessary for complex offshore structure investigations.

The model ice is produced from carbamide doped water by an air forced cooling system, which provides a freezing rate of 2.5 to 3.0 mm/h at an air temperature of -25 °C.

The ice cover is uniform over the entire test area with variations of ± 1 mm. Also the ice strength properties are constant over the length of the ice tank with variations of 5% to 10%, which lies within the range of the measuring accuracy.

In addition to conventional model test projects, the dimensions of the new ice tank and the experimental equipment allow for the performance of self-propulsion and manoeuvring tests with ice-breaking ship models and the simulation of tower moored barges, artificial islands, multilegged or conical structures in ice conditions such as level ice, rubble ice, ridges (first and multiyear), ice floes, mush ice, brash ice and icebergs.

The actual model test in the ice basin actually makes up only a small part of the efforts involved in conducting model tests. A major part is dedicated to the controlling and investigating the ice properties. Besides the standard cantilever beam tests and deflection measurements of the ice cover for establishing the E-modulus, compressive strength tests, friction tests, and internal shear tests of broken ice in a shear box are all being requested in order to establish a complete picture of the test conditions. For these supplementary tests, HSVA is at present constructing a second refrigerated ice laboratory.
One can hope that with these new ice testing facilities, the simulation of ice engineering problems will be improved.

REFERENCES


Fig. 1: Fracture toughness $K_{1c}$ vs. flexural strength and scale factor, $\lambda$, for urea doped model ice (after Timco /9/)

Fig. 2: Size of ice floes in channel broken by the POLARSTERN (model test)
Fig. 3: Crushing failure of level ice penetrated by vertical column

Fig. 4: Multilegged structure in level ice with ridge
Fig. 5: Model of Conical Drilling Unit, "KULLUK", penetrating a ridge

Fig. 6: Arrangement of tower moored barge system in HSWA's ice tank
Fig. 7: Lay out and cross section of HSVA's new ice model basin

Fig. 8: HSVA's new ice model basin
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THE NORTHERN SEA ROUTE : ITS PAST, PRESENT, AND FUTURE

The Northern Sea Route is an important, national transport line of our country, which has played a decisive role in the political, economic, and cultural development of the Soviet Arctic. Navigation in the arctic areas has changed beyond recognition. The material and technical basis have been qualitatively changed and as a result sailing tactics have been changed in the high latitudes. Already, we have made some progress but we must make some more. We can really appraise the present situation and future development of the Northern Sea Route. It is only a short time ago* that our country started to study how to navigate in the Arctic Sea which is adjacent to USSR northern coast.

* More details about this story, you can read in the author's book "Soviet Arctic transport waterway", which was printed in 1984 by "NAUKA" publishing house.
The Past

Formation of the Northern Sea Route as a transport line was very difficult, especially during the opening chapters of history. This process was born in a prolonged struggle between supporters and opponents of the practical usage of this sea route. Today, when we can see this process lasting tens and hundreds of years, we clearly realize that resistance to arctic navigation from the opponents was only partly of a subjective nature - for example, certain improvidence of some statesmen of tsarist Russia. Such things, of course, have been in practice. In addition, the struggle of ideas round the Northern Searoute also had an objective nature linked with features of this sea route. Hereby, we mean, features that heighten the significance of the Northern Sea Route for our country:

The first feature of the Northern Sea Route is that it stretches from the Novaya Zemlya strait along our country's coast to the Bering Strait and therefore, it is irrespective of international situation at any time. Besides, it is the shortest seaway between our western and eastern ports. For example, the distance between Murmansk and Vladivostok through the Suez Canal is about 12,800 miles, but along the Northern Sea Route - about 5,800 miles. Such an evident geographical advantage of this route is the first argument of its enthusiasts.
The Northern Sea Route stretches along the mouths of the largest North Asian rivers: The Ob, the Taz, the Pur, the Yenisei, the Pyasina, the Hatange, the Lena, the Yana, the Indigirka, the Kolyma which turn to meridional direction and are formed by large and small rivers and create a broad network of inland water ways. Russian people well understood that such a network can open the road to natural resources of a vast territory which stretches to the centre of the Asian continent. This circumstance became the second "perpetual" argument of the Northern Sea Route supporters.

But the Northern Sea Route advantages which seemed so obvious at first sight were found to be not so convincing for the simple but very serious reason: hard old giant icefloes from the Novaya Zemlya to the Bering Strait hampered free sailing. This ice became, figuratively speaking, the main line of active defence against the attack of Man's curiosity to study the Northern Sea Route.

However, ice and hard frost of polar seas couldn't stop Russian dare-devils, who from time immemorial have dared to explore the Arctic and investigate the navigation possibilities through the Northern Sea Route. For this clear purpose, step by step, many generations of Russian people have gone through a hard school of experience and have stored knowledge about this huge and harsh land. There they met with cold weather and cover of polar night, gnashing of compacted ice, torments of chronic underfeeding, inevitable scurvy with not infrequently a fatal outcome. We shall not touch upon the purely human side of people's skirmish with the arctic nature but only draw your attention to such historic details which illustrate the development of the Northern Sea Route as transport line.

The beginning of the great sea travels to the East was made by Russian pomers (people living in the Northern European areas of the country) who had a great deal of experience sailing on seas covered with ice. In the 16th century, using small boats (kochas), they made voyages to the Novaya Zemlya, Spitsbergen, the mouths of the Ob and Taza Rivers, and in the 17th century they reached the mouths of the Yenisei, the Lena and the Kolyma. In 1648, a detachment of Semyon Dezhnev travelled from the Kolyma to the Bering Strait, thus concluding the discovery by Russians of the Asian coast of the Arctic ocean. In this way, it was proved
that there existed a sea route from the Atlantic Ocean to the Pacific.

During the first quarter of the 18th century, Russia emerged as one of the major sea powers, and Peter I became the initiator of organizing the Great Northern Expedition. In 1732-1741, after the death of Peter I, five detachments travelled along the Northern regions of Russia from Arkhangelsk to the Kolyma, making the first survey of the sea coast. Later, in 1785-1792, the North-Eastern Expedition travelled along the northern coast of the Chukotka Peninsula. As a result, general maps of the Northern coasts of the Russian Empire were drawn.

The geographic notions of the Northern Sea Route were enriched in the 19th century through the work of Russian expeditions headed by F. Litke, P. Pakhtusov, A. Tsivolka, A. Bunge, and E. Toll. The expedition, headed by F. Wrangel drew the first map of the Siberian coast from Shelagski cape to Koluchinski inlet in 1821-1824, which made a significant contribution to its study.

In 1910-1915 Russia organized the big Hydrographic Arctic Ocean Expedition, using for the first time two steamships of ice-class, "Taimyr" and "Vaigach". Maps showing the geographic situation of the Northern coasts were very precisely made by that expedition and a number of discoveries were made, including the discovery in 1913 of the large archipelago, Severnaya Zemlya. The work of these expeditions permitted the drawing of new general maps of the Russian Arctic and obtained the first systematic data on sailing conditions in Arctic seas.

Along with the study of the Northern Sea Route, commercial voyages were organized on the western and eastern flanks. The so-called Kara Sea Route from the West to the mouths of the Ob and the Yenisei became especially popular. 115 ships travelled by that route from 1876 - 1917 and over 70,000 tons of various cargo were transported. Besides, from 1911 - 1917, seven commercial voyages were made on the eastern flanks of the route from Vladivostok to the mouth of the Kolyma. Thus Russians laid the foundation to the commercial navigation along the Northern Sea Route.

From time to time, the government and public circles of Russia analyzed a possibility of organizing voyages along the Northern
Sea Route. This is why the Russian government welcomed the idea of organizing the Swedish-Russian expedition headed by A. Nordensheld. He travelled on the steamship, the "Vega", along the whole Northern Sea Route from the West to the East in 1878-1879, which took him two navigation periods and one wintering. The same task was accomplished by the steamships "Taimyr" and "Vaigach" in 1914-1915, when they sailed from Vladivostok to Arkhangelsk, i.e. the opposite direction, also with one wintering. After these two trips, people held a pessimistic point of view on the possibility of voyages along the Northern Sea Route. Only transport availability of the Yenisei's mouth from the West and the Lena's mouth from the East was optimistically estimated. In our time, we can say that such a standpoint reflected the real situation and corresponded to marine technology at that time.

Even from this short story, we can see that the problem of Arctic navigation occupied an important place in the life and deeds of the Russian state. It was difficult to find a solution as the enthusiastic desire of Russians to develop the Northern Sea Route confronted with the powerful bastion of ice restrained by poor development of shipbuilding in spite of the Pomers' good kochas (small boats). With such marine technology, it was impossible to develop the Northern Sea Route. Major technical knowledge for using the Arctic route emerged by the end of the 19th century and the beginning of the 20th century. Sailing ships were replaced by transport vessels with metal hulls and comparatively powerful engines. In 1899 Russia built the first powerful icebreaker, Ermak, with a capacity of 10,000 h.p., a good capacity at that time but not enough to sail in arctic ice. During World War I, a whole fleet of icebreakers was formed which included 24 icebreakers and steamships of ice-class. The fleet operated successfully in the White Sea where Russian seamen gained wide experience in ice shipping. Later, this experience was effectively used for developing the Northern Sea Route. In 1916, port investigation started in the mouth of the Yenisei and a telegraph set was installed at the west flank of the Northern Sea Route. In 1915, the first plane was tested in the Arctic. As we see, the beginning of the 20th century saw individual, though poor sprouts of what we today call the system of the Northern Sea Route.
The Present

After the October Revolution of 1917, Russia continued to develop navigation in the Arctic seas. An exhausting civil war led to unfortunate results. During the first peaceful years of Soviet power, it was necessary to begin development of Arctic navigation anew.

The first initiatives of the Soviet Government in this sphere were connected with the Kara Sea Route by which already in 1920 grain was transported from Siberia to the starving population of the European part of the country. In the 1920s, thanks to the consistent and steadfast decisions of the Government, Kara Sea operations were organized which ensured the transportation of goods from Europe to Siberia and the transportation of timber and grain from Siberia back to the European regions of the USSR. By the early 1930s about 314,000 tons of cargo was transported by the Kara Sea Route. This became possible by using icebreakers, organizing plane ice observations, weather- and ice forecasts and regular radio communication. These combined measures prolonged the navigation period in the Kara Sea from 20 - 30 days in the early 1920s to 2 - 2½ months in the 1930s.

In the Eastern flanks of the Northern Sea Route, measures were also taken to organize navigation. From 1923 - 1932, annual voyages of merchant ships were organized from Vladivostok to the Kolyma. From an economic point of view, the Kolyma voyages were of small importance, for the total volume of cargo transported by them was a little over 10,000 tons. However, in principle, they confirmed the possibility of organizing regular ship voyages along the coast of the Chukchi and East Siberian Seas.

Accomplishments in the development of the flanks of the Northern Sea Route as well as the expansion of socialist development in the North of Siberia were the main reasons why early in the 1930s, the question was brought up of organizing a transport communication line on the entire Northern Sea Route. But at the time, some supporter of high latitude railway construction were against the idea. In order to put an end to the polemic and to determine the possibilities of the exploitation of the entire Arctic Route, the Government in 1932 approved a plan for a voyage of the "Sibipyakov" icebreaking steamship from Arkhangelsk to the Bering Strait. The task was accomplished in one navigation period (in 65 days).
When the debate was over, the question arose of how to develop the whole of the Northern Sea Route quickly and effectively. Proceeding from the accumulated experience, it was decided that Arctic sea operations should be organized on a national scale and that various specialists - sailors, hydrographers, communication specialists, pilots and scientists - should pool their efforts in implementing the task. A special body was set up in 1932 to tackle this problem - the National North Sea Route Agency* under the Council of People's Commissars of the USSR.

In the 1930s, the Agency carried out a large amount of work. The designing was started of new Soviet icebreakers with a capacity for 10,000 h.p. which were put into service from 1938-1941. In those years, the first transport vessels of the icebreaker type were built, featuring large weight-carrying capacity and strength. Port and bases of the Northern Sea Route - Dikcon, Tiksi, Pevek, Provideniya - were built one after another. The hydrographic fleet was also increased, which permitted the start of a systematical study of the relief of the bed of Arctic Seas. A network of hydro-meteorological stations and radio centres was created along the Northern Sea Route. The Arctic Institute started the development of methods of weather- and ice forecasting on the Northern Sea Route. Ice reconnaissance by planes was put on a regular basis.

It was not long before the results of all these efforts manifested themselves. Already in 1940, the share of cargo transported by sea to the areas east of the mouth of the Yenisei amounted to 48%. The average length of a navigation period in 1935 - 1940 was 107 days in the western part of the Northern Sea Route and 79 days in the eastern part. Rational scheme of cargo transportation in the Arctic zone, taking into account ice conditions, was determined. Accumulation of experience and clear directions of Arctic marine operation staffs contributed to efficient organization of ice shipping. As a result, unpleasant surprises were considerably reduced. Thus a 30-40 year-period in search of methods of developing

* Later, in the 1950s the Agency became part of the USSR Ministry of Merchant Marine and is functioning today as the Administration of the Northern Sea Route.
the Northern Sea Route was over; the Route assumed the character of a reliable summer transport line.

After World War II the Soviet Union continued to develop the Arctic zone. In order to solve the problem, our country ensured a further steady development of all elements of the Northern Sea Route system: a fleet of icebreakers, ships for the navigation in the ice-covered waters, port equipment, as well as navigation, hydrographic, scientific and aviation facilities.

The main emphasis was laid on the development of the powerful icebreaker fleet. Old icebreakers with a capacity of only 10,000 h.p. were useless when the route was blocked by heavy ice; convoys had to wait for improvement of the ice situation. This circumstance became more unfavourable with the increase of the total shipping volume. That is why since 1959 the "Lenin" nuclear-powered icebreaker with a capacity of 44,000 h.p. has been working in the Arctic. In the 1960s, it was joined by a series of icebreakers of the "Moskva" type with a capacity of 26,000 h.p. each. In addition to ships of the "Lena" and "Dneproges" type built in the 1950s with increased icebreaking capacity, merchant ships of the "Amguema" type of Arctic ice class were put into operation. As a result, consolidated ice ridges that earlier were believed to be impassable began to be forced. Fast ice around more marginal points of the Arctic - the Yenisei Bay, the Vilkitski Strait, the Sannikova Strait, the Chaunskaya Bay, the Schmidt cape - were successfully broken up by icebreakers. This made it possible to steer ships to the ports of destination in a shorter period of time and created conditions for repeated voyages. Such approach permitted a more effective use of the transport fleet and of the port facilities.

The development of Soviet Arctic industrial centres involved in the 50-60s the construction of new Arctic ports: Amderma, Khatanga, Zeliony Mys, Schmidt. In order to increase effectiveness of the Arctic fleet, mooring lines and mechanical equipment were improved in departure ports: Murmansk, Archangelsk, Kandalaksha, Vladivostok and others. During the last decade, port facilities in Yamburg and Kharassavey were modernized because of exploitation of the Yamals hydrocarbon resources.
A hydrographic enterprise secured the fleet operation. Its local branches, so called hydrographic bases, carried out a regular sounding of the sea-bed's relief from ships in summer and from the ice in winter. The hydrographic fleet has changed enormously. "Peter Pachtussov" and "Georgui Sedov" were the first hydrographic icebreakers built in 1967 especially for survey. Since 1970, hydrographic works were carried out on ice-strengthened ships of the "Dmytriy Ovssyn" class supplied with high-precision sounding complexes. Today, navigable lines of the Northern Sea Route have modern navigational aids, including high-quality radionavigational and satellite systems. Nautical charts and sailing directions about Arctic seas are constantly renovated and corrected. Any change of shipping conditions is reported to navigators immediately. The Arctic and Antarctic Research Institute experts worked out a scientific basis for ice reconnaissance in Arctic seas. They elaborated sea ice nomenclature and visual evaluation methods for determining different ice characteristics which limited navigation. The strategic ice reconnaissance has become regular. It was carried out after a standard scheme of flight during the year once a month in winter and once in a ten-day period in summer. The tactic ice reconnaissance is executed by more frequent trips in these areas where traffic is intense. These data were supplemented with information about the ice distribution collected from helicopters based on icebreakers' decks and from satellites. Results of these observations were fixed on general maps of the ice distribution in all Arctic seas at a certain time. Today, we have the largest series of ice observations and we see clear enough the natural conditions of Arctic shipping.

Ice reconnaissance data, observations on drifting stations "North Pole", information from numerous maritime and air expeditions are used for ice forecasts and for various handbooks and monographs. The science of long-term forecasting proceeds in accordance with demands for Arctic navigation. Long-term forecasts of the ice conditions made in January, March, and August have become a necessary component for the plan of ships and icebreakers placed in the Arctic. The number of predicted indicators amounts to 600 and their average justification is more than 80%. The planning of specific sea operations is based on ice forecasts of 1-10 days in
advance. The justification for these is about 90%. Ice- and weather forecasts and following these navigation guide-lines represent the achievements of the scientific development to secure Arctic shipping.

Owing to the shipping intensification along the Northern Sea Route, the question arises about the protection of waters from pollution. A number of measures is adopted to solve this problem:

1. All domestic ships going to the Arctic possess a special water-protecting equipment.

2. The inspectors of the Administration of the Northern Sea Route keep under observation the execution of the measures on vessels<sup>1</sup>) from planes and helicopter. The offenders<sup>2</sup>) are punished, for example, penalty is imposed or the driving licence is taken away.

3. The experts of the Arctic and Antarctic Research Institute carry out a regular assessment of the pollution's level in Arctic waters aimed to detect the sources of pollution and to study its dynamics.

4. A great deal of work is done to investigate the distribution of the main chemical elements in Arctic seas and their role in chemical, physics, and biochemical processes; this work will help to solve the problem on a scientific basis.

5. Measures are taken<sup>3</sup>) to protect inland waters since many rivers flow along industrial centres northwards into the Arctic Sea.

Thanks to these measures, the level of pollution in Soviet Arctic seas keeps steady below critical concentration.

Remarkable achievement of Arctic navigation on the one hand and on the other hand the development of great industrial centres in western regions of Soviet Arctic, Norilsk in particular, resulted in the organization of an autumn-winter shipping in the Kara Sea during the 70s. Trial voyages in 1970-71 of one-two escorted steamships were successful. Then, we started an experiment on a basis of

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1) On all vessels without regard to their belonging department or State
2) Decree of the Supreme Soviet of the USSR
3) Decision of CC CPSU and Council of Ministers from 15.01.1981
cargo transportation. However, exceptionally severe ice conditions during 1972 winter navigation caused an interruption of plans.

Seamen and scientists learned many lessons during this winter navigation and the next one, each having unique particularities. The need has emerged of putting into operation more powered icebreakers and more strengthened vessels.

The experience from winter ice-going navigation of using powerful nuclear icebreaker of "Arktik" type and of shallow-drought diesel-electric icebreaker "Kapitan Sorokin" type which provide the escorting in off-shore and river sectors of Dudinka line accordingly permitted a step by step prolongation of the winter season and from 1978 a year-round navigation to Dudinka. Transportation in winter has become safer thanks to the construction of specialized ice-strengthened transport ships: tankers of the "Samotlor" type, bulk carrier of the "Dmytryi Donskoy" type, multipurpose vessel of the "Norilsk" type. Both navigation-and-hydrographic aids and weather-service with its accurate forecasts support the reliability of the year-round transport conveyor. The role of ice reconnaissance is especially important. It takes into account poor visibility during the polar night by a development of instrumental methods of ice evaluation: radio-locating, infra-red, laser, TV-set.

Step by step, activity aimed to solve the complex problems of Arctic navigation has good results; annually, hundreds of various vessels are ploughing the Arctic seas. Soviet Arctic has changed beyond recognition, its unique natural resources are successfully involved in the industrial development. Today, thousands of Soviet people work in towns and settlements provided with modern conveniences. We can surely say that the problem of territorial isolation of this region is solved.

The Future

Before speaking about possible prospects of the Northern Sea Route development, we must objectively without needless colouring

1) "L.Breznev" today
assess our achievements. The main result is the obvious trend of a considerable prolongation of the navigation season. That is good, but to achieve this result was not easy. To extend the season for a month or even for a week, we have to improve the material and the technical basis of the fleet. Therefore, a structural modification of the fleet operating in the Arctic was necessary. The capacity of the icebreakers "L.Brezhnev" type is 75,000 hp, the ships of the "Norilsk" type are capable of breaking 1 m of ice without assistance, their specific power is up to the level of the 3 - 4 icebreaker class which operated in 30 - 50 years, i.e. on the early stage of the Northern Sea Route development. As we see, a large distance was overcome. It is clear that this radical modification demands serious expenses. Must we run the risk?

In this case our main criterion is the national-economic efficiency of transportation. Certainly, the economic characteristics of winter operations are larger than those of summer. On the other hand, owing to the extension of the season, there is a considerable economy of capital and operating expenses for industries supplied by the fleet because of reduction of current assets, of warehousing space, mooring sites and loading complexes. We have reduced losses from deterioration during prolonged storage of cargo. There is a considerable reduction of deliveries by airtransport. If we summarize all "for" and "against", we see there is more "for". Such arithmetic depends mainly on the traffic volume which is necessary to transport in one or another direction: if it is possible to handle the freight without pressing in summer, there is no sense to do it in winter running severe risks.

It goes without saying, we have a lot of difficulties due to the aggravation of conditions for freighting in winter. First of all because the large amount of ice increases the probability of ice pressure and this is the greatest obstacle to shipping. From summer to winter the average wind speed increases and as a result heavy ice compacting occurs. In the winter, ice compacting along waterline level of ships form an ice pad = adhesion of ice pieces to the hull. The length of such a pad can attain 4 - 50 metres. It is not easy of course to sail with such a load. Besides, the strength of winter ice is much greater than that of summer, so the probabi-
lity increases of damage to ships. The overall picture of the fleet's operations in winter would not be complete without mentioning the deterioration of the visibility, severe frost, and penetrating winds.

Ice conditions on the Kara Sea both in summer and in winter are the easiest along the Northern Sea Route. Eastwards, difficulties are more serious. In those areas, according to evaluations of our experts, it technically will require capability to continuously break the ice 250 - 350 cm thick under ice compacting of 2 - 3 degrees. Is this possible or is it not?

To answer this question, a number of experimental voyages by nuclear-powered icebreakers have been made in extremely heavy ice conditions. The most famous among them are the nuclear-powered vessel "Artika's" voyage to the North Pole in August 1977 and the nuclear-powered vessel "Sybyr's" voyage in May - June 1978. The first was an autonomous cruise; during the second, "Sybyr" escorted "Kapitan Myschevski", a transport ship, through the high latitude way from Murmansk to Bering Strait. In the course of the trips, the ice-breaking capability and reliability of their technical systems were studied in hard ice conditions. The experience has shown that the prolonged navigation eastwards of Yenissey's estuary is feasible but to do that the capacity of icebreakers must be increased up to 130,000 - 150,000 hp. However, it involves additional expenses of freighting. Is it worth taking them? Perhaps there are alternatives to a solution of the transport problem in the Arctic.

Surely we do not abandon the prospect of other kinds of transports than the active ice-going fleet. First of all, we are thinking of pipelines for delivery of oil and gas in the future. In the coming 20 - 30 years railways will be built up to Yamburg, Yakutsk, and Norilsk, and these important factors will seriously affect the transport scheme of the Arctic zone. The possibilities of navigation extension in the Arctic water areas of the Ob, the Khatanga, the Lena, the Indigirka, and the Kolyma rivers are only limited in October to November due to their shallow estuaries. The development of motor and air transport will continue. However, the analysis shows that despite the other transport developments in the Arctic, the problem of the shipping season prolongation along all of the Northern Sea Route still exists.
The future of the Northern Sea Route as a technical system will be determined by the economic orientation of its use:

1. Transportation for the extractive industries in the Arctic.
2. Traffic between the western and the Far-eastern ports of USSR.

Each of these two factors has its specific feature: Concerning the first one, there is the presence of coastal shallow lines; concerning the second one, there is the presence of high latitudes and deep-sea water-ways. Therefore, each of them demands a structure of the fleet specially adapted to its requirement.

What place will the icebreakers have in this structure? In our country we study various possible ways of destroying the ice cover: mechanical or by heat. The area where ice destruction by heat (radiation, chemical methods and so on) can be used is limited in the Arctic owing to prevalence of drift ice; it may only be applied to solve local tasks in the fast ice. As for mechanical ones - we seek to improve the traditional icebreaking method - the precision of the hull's shape, devices for reducing the friction between ship and ice (air-operated device, special paint coats for underwater body). We study the possibilities for using large-capacity vessel of icebreaker type and transport submarine in the Arctic. Keeping in mind the possibilities of creating completely new technological marine systems for the Arctic, we assume that in the nearest two or three decades the icebreaker-ship system i.e. shipping behind an icebreaker will remain dominant.

We understand that it would not be wise to base our relations with arctic nature on the icebreaking capacity. Energy resources including nuclear ones have their limits. We can win a victory with a head-on attack, but it is not enough. It is necessary that the victory should not be very expensive. In such an approach we see the economic side of the arctic navigation problem.

The economic advantage and the efficiency, i.e. total net benefit to be gained in the Arctic are the criteria for the economic justification of further development of the Northern Sea Route system and of the extension of the shipping season in other sectors of the transport connections.
Enormous mineral resources are concentrated in this harsh region. Therefore, the advance of the industry northwards represents an objective process depending on the demands for our economy. In order to extract 1 ton of valuable mineral in the Arctic, hundreds of tonnes of cargo are required as vehicles, equipment, materials, building structures, manufactured goods and foodstuffs. That is why we have our reason to believe that white-and-blue lines of the Northern Sea Route will become an important way of transporting cargo in the future.
Polar Lows - A Threat to Offshore Operations in Northern Waters

Background

Everybody knows what a hurricane is, but surprisingly few know that the tropical cyclone has an arctic cousin (and no doubt an antarctic one as well). Arctic lows, instability lows or polar lows as we shall call them, are small but intense lows forming in arctic or subarctic areas. Typically their size is 100 - 500 km or significantly less than the 1000 - 4000 km diameter of a regular extratropical cyclone.

Storm characteristics

Apart from their small size and the areas to which they are confined, polar lows have several characteristics that tend to make them dangerous.

1. High winds (gale to hurricane strength).
2. Rapid increase from zero to storm (~15 minutes)
3. Heavy precipitation (snow, hail)
4. Severe icing (sea spray at low temperatures)
5. Accompanying steep waves and confused sea
6. Frequently unpredicted

There is a general lack of exact information on polar lows. They are formed in an area with few meteorological stations, and therefore they have in the past slipped through unobserved. They travel at speeds typically in the range 10-20 knots and frequently arrive unpredicted in storm-prone areas like the coast of Northern Norway, in contrast to storms from west or south that are normally predic-
ted well in advance. Accordingly, the polar lows have in the past caused disasters, as the low hitting and sinking MS "Uvik Senior" near Senja in February 1978 (Fig. 1).

Fig. 1. Track of the storm that hit "Uvik Senior"
The primary reason for bringing up these phenomena for study now is the advance into the storm-prone areas of the petroleum industry and the extension of operations here from seasonal to all-year. A secondary reason is the development of new observational tools like satellite imagery and specialized radar making surveillance, data acquisition and data dissemination feasible. Thus the timing is based on an urgent need for information as well as on new opportunities for observing the storms.

The active period of the Polar Lows Project was 1982-85, and the results will be presented at an open symposium in May 1986.

**The Polar Lows Project**

A three year programme has been sponsored by the Norwegian oil companies STATOIL, NORSK HYDRO and, through the Operators Association, a number of international companies holding licences north of the 62th parallel. The project has activated research groups at many institutions: The Norwegian Meteorological Institute, Oceanor, The Norwegian Hydrotechnical Laboratory and the universities in Oslo, Tromsø and Copenhagen. Valuable US air reconnaissance flights through polar lows were staged from Norway by NOAA. The work has been broken down into 7 subtasks:

1. Climatology based on historic weather maps and satellite imagery.
2. Case studies of storms occurring during the project.
3. Dynamic models - prognostic, mesoscale
4. Statistical models - trajectory prediction
5. Improved forecast - satellite images, drifting buoys
6. Ocean surface waves - evidence in wave records of PL's
7. Laboratory wave study - waves trapped by a moving wind field
The threatened area

A necessary but not sufficient condition for a polar low to develop, is a destabilized atmosphere. This comes about when cold air is heated from below (Fig. 2). The typical situation is a massive outbreak of -20 to -40°C cold air, from the polar ice cap or from the surrounding cold continents, flowing out over an open sea. The ocean surface even at its freezing point of -1.9°C is a fairly strong heat source, giving off a few hundred watts per square metre. In the European Arctic the North Atlantic Current pushes warm water up towards the ice, enhancing the heat flux with surface temperatures up to +5°C.

Thus the polar low hazard to Norwegian waters is associated with winds out of the sector NW through NE.

![Fig. 2. Destabilizing of the atmosphere by heating from below.](image)

Occasionally the outbreaks carry polar lows as far as the Northern North Sea. In any case it is clear that these storms, even though they are by definition north of the polar front, may range over a vast ocean area (Fig. 3).

On the other hand the polar low dies quickly after a landfall. It creates havoc on the Norwegian coast, but it has only been reported once in Sweden.
The triggering mechanisms

From an operator's point of view it doesn't make much difference whether a viscous storm is generated by this or that mechanism. The importance of a study of the cyclogenesis is that an understanding of it gives the forecaster a clue, and hopefully, a tool. So far four mechanisms have been identified.

1. Topography Obstacles like mountains generate vortex streets downstream. These well known Karman vortices sometimes roll up into larger eddies. The interesting question why this constant topographic forcing only now and then results in a polar low is unanswered at present. Nevertheless the mountains of Svalbard, Jan Mayen and Iceland are sometimes breeders of storms.

2. CISK (Conditional instability of the second kind). This name refers to an instability which is fed by the convection in the centre of an eddy and the associated convergence in the lower layers. The mechanism is similar to the classical hurricane model of a storm with a warm core, driven by the rising warm and moist air. An important difference between the polar and the tropical storm is that the release of latent heat is the dominating driving force in the latter case while in the polar low latent and sensible heat are both important.

3. Differential heating near the coast/ice edge It is not uncommon that cold air flows parallel to the ocean boundary, which may be a coastline or an ice edge. The resulting differential heating sets up a horizontal shear and momentum transfer. Perturbations of the air flow may become unstable under this shear and develop into vortices that may become polar lows.

4. Main air stream shear Some polar lows have been observed to have cold rather than warm cores. These cyclones are the result of baroclinicity, shear and vortex generation in the upper layers. When such a vortex is started aloft, its core is cold and remains so when the vortex penetrates downwards.
In the final analysis there can only be two sources of energy for an atmospheric storm: 1) The potential energy of the atmosphere itself, provided there are horizontal gradients at some level (baroclinicity), and 2) Heat flux from the ground (CISK). It appears, from the observations as well as from the simulations, that the polar lows require triggering. The interplay between a trigger mechanism, say a Karman vortex street, or differential heating, and the feeder mechanism supplying energy, is still largely unknown.

Some preliminary results

The final report has not been written yet, so it is premature to present results here. However, some of the sub-prosjects have produced conclusive results that are released.

Climatology

The sample of the 71 lows with landfall in Norway during the 11 year period 1972-1982 has the distribution shown in Fig. 4. The dip in February reveals a two-peak distribution. Perhaps more significant is the observation that polar lows have occurred in every month except July and August.

The storm tracks are shown in Fig. 3. It is interesting to observe that many polar lows follow the coast, a fact that makes warning easier.

The general impression Fig. 3 conveys, is one of randomness and unpredictability. An attempt to predict trajectories by a model based on past track histories proved futile. This does not rule out predictors based on other information such as an advection wind speed.
Fig. 3. The track of polar lows 1978-1982.

Fig. 4. Frequency distribution of polar lows 1972-1982 (71 cases in 11 years) in the Norwegian Sea and the Barents Sea.
Dynamic models

The normal grid of DNMI's operating prognostic model is 300 km, which is too coarse for mesoscale phenomena like polar lows.

An experiment with the same model using a 50 km grid gave encouraging results: While the hindcast failed to reproduce the observed polar low in the 300 km grid, the cyclone was reproduced in the 50 km grid. Routine numerical forecast of mesoscale storms is now attempted.

Operational forecasting

Polar lows have a cloud-top signature that makes their detection feasible, at an early stage of their development, on satellite images. A potential storm is revealed by its "comma" cloud, which can be monitored on images from successive satellite passes. A developed polar low is seen in Fig. 5.

The observations of air pressure from an increasing number of drifting (or anchored) buoys in the Norwegian and Barents Sea have proved of great value in the forecasting.

Weather radar is recommended as a promising tool in the detection and monitoring of polar lows. The range is about 300 km, which gives about 12 hours lead time. Information on wind speed is also obtained.
Fig. 5. Satellite picture 1030 GMT, 19 April 1983.
(NOAA 7, Ch 2, Tromsø, Norway)
a linear course, the waves that remain inside the low are located to the right of the low as indicated in Fig. 6.

In addition to this directional filter there is also a speed filter at work as explained in Fig. 7.

Consider the "fetch" for a wind field of length $L_0$ moving with a velocity $V_L$ along a straight course, beginning at time $t = 0$ in position $x = 0$.

At time $t_1$ the "low" is in position $x_1 = V_L t_1$. Not all the waves that were in the storm at $t = 0$, are still in it at $t = t_1$. Some waves have travelled ahead of the storm, while others are left behind. Waves with group velocity equal to the speed of the low $V_L$ will not change their position relative to the wind field. The packet of waves that has not yet left the wind field at time $t_1$ has group velocities

$$c_g = V_L \pm \frac{1}{2} \frac{L_0}{t_1}$$  \hspace{1cm} (1)

From (1) it is seen that the movement of the storm acts as a filter for the waves. The shorter the "fetch" $L_0$ of the storm and the longer its "duration" $t_1$, the more selective is the storm.
Recorded ocean waves

After one of the subprojects had disclosed historic trajectories of polar lows, another subproject scrutinized those historic wave records that might contain waves generated by polar lows. The study included between 30 and 40 such records obtained by various wave buoys off the coast of Northern Norway.

A preliminary finding is the milder slope ($f^{-4}$) of the high frequency side of the power spectra for these wave records compared with the commonly obtained $f^{-5}$ relation. No narrow spectra were observed.

Laboratory experiments

The first season of observations in the Polar Low project brought no information on waves, and it became obvious that sufficient new data from the sea would be hard to obtain within the three-year project. On the other hand some laboratory experiments might throw new light on the waves under a moving wind field. The fact that nobody seemed to have attempted such tests encouraged us to try.

Accordingly, we designed a simple experiment with a short (15-20 m) wind field moving with the towing carriage down the 250 m long towing tank at the Ship and Ocean laboratory in Trondheim. The tank is very well equipped for its intended purpose. For instance, wave records are easily obtained and processed on line to deliver wave parameters, power spectra etc. However, our test was not a conventional one, and our budget was very tight, so we had to improvise.

The wind field was made up of a battery of fans (Figure 8) mounted on the towing carriage. This simple solution was chosen after several ideas of bottomless wind tunnels etc had been discarded. The resulting wind field is seen in Figures 9, 10 and 11. The wind is fairly evenly distributed across the 10.5 m wide channel (Figure 9). The reduction with distance from the fans (Figure 10) is linear until the speed is halved at about 18 m. Beyond 20 m the wind speed is too low for further forcing of the waves as $U/c \sim 1$ where $c$ is the phase speed of the waves.
The vertical wind profiles shown in Figure 11 were measured down to 0.3 m above SWL. The increase from 0.5 m to 0.3 m is small, and the latter values may be taken as maxima, or \( U \) for comparison with stationary wind fields. A reasonable average value is \( U = 7 \) m/s.

Fig. 8. Positions of fans on towing carriage.

Fig. 9. Average wind speed 4 m from fans.
Fig. 10. Average wind speed.

Fig. 11. Vertical wind profiles
Fig. 12. Time series and spectra for a specific run.
EXPERIMENTAL RESULTS

Wave records

While the experimental wind field travelled down the length of the tank, the waves were recorded at four fixed positions, after 31, 76, 126 and 176 m, as well as on the carriage. A sample of each record is shown in Figure 12.

The wave records confirm the visual observation of groups, but they also reveal that the groups did not have a constant length equal to the length $L_0$ of the wind field. It seems that what we observe is the process of intermittent grouping, disappearance and regrouping that is required to accommodate fewer and fewer waves as their period and length increase (Plate, 1978). This beat-like behaviour appears to be the kinematic trick played by real waves in a situation of growing with little or no wave breaking.

With so few waves in each group it was difficult to extract a representative wave height. The mean value would depend critically on the number of waves averaged, and the maximum value would also tend to be uncertain. By contrast the wave period showed very little variation within each group.

The power spectra in Figure 12 must be seen in this light. They are based on a very small number (12-15) of highly amplitude-modulated waves, so too much should not be read into them. They are narrow-banded, but not mono-chromatic spikes. In fact, their frequency range is about the same as for laboratory waves generated by a stationary wind (Plate, 1978).
Comparison with waves generated by stationary wind

The classical prediction equations for stationary wind fields are:

\[ t = k_1 \frac{F^{2/3}}{\sqrt{f}} \]

for the relation between dimensionless time, or duration of the storm,

\[ t = \frac{gt}{U} \]

and dimensionless fetch

\[ F = \frac{gF}{U^2} \]

The peak period is related to fetch through

\[ f_p = k_2 \frac{F^{-1/3}}{\sqrt{f}} \]

with

\[ f_p = \frac{uf}{g} = \frac{U}{gT} \]

From these expressions we derive

\[ T_p = \frac{1}{k_2} \frac{Ut}{k_1 g} = a/t \quad (2) \]

for duration-limited waves and

\[ T_p = \frac{1}{k_2} \left( \frac{U}{g^2} \right)^{1/3} F^{1/3} = bF^{1/3} \quad (3) \]

for fetch-limited waves. A fitted curve yielding \( a = 0.064 \) (Table 1) is drawn in Figure 13 and a fitted curve yielding \( b = 0.17 \) is drawn in Figure 14. These coefficients are higher than those obtained with the published values \( k_1 = 71 \) and \( k_2 = 3.2 \). (Hasselmann, 1973 and Mitsuyasu, 1980). Inserted in (2) and (3) the coefficients for a stationary wind become \( a = 0.031 \) and \( b = 0.13 \), respectively. The variations in the coefficients \( k_1 \) and \( k_2 \) from various experiments are approximately ± 10 %.
The uncertainty in the relevant wind speed to use in the formulas will introduce an uncertainty in the derived coefficients, but we have to use a wind velocity of 30 m/s to get the same values for a and b that are reported in the literature. If we assume a logarithmic wind profile we have $u_{0.25}/u_{10} = 0.6$ through the lowest point observation at $z = 0.25$ m. This would indicate a $u_{10}$ of max 13 m/s, which is still too low to explain the differences.

Fig. 13. Wave period vs travel time.

Fig. 14. Wave period vs travel distance.
Table 1. Summary of results from 4 runs.

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<th>$V_L$ (m/s)</th>
<th>X (m)</th>
<th>t (s)</th>
<th>T (s)</th>
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<th>n = t/T</th>
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<td>0.94</td>
<td>230</td>
<td>0.065</td>
<td>0.175</td>
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</tbody>
</table>

Figure 13 is a plot of observed wave period $T$ versus travel time $t$ while Figure 14 shows $T$ versus travel distance $x$. Equation (2) with the experimental value $a = 0.064$ and the value $a = 0.031$ for constant wind is drawn in Figure 13. Similarly equation (3) is shown in Figure 14 with the experimental value $b = 0.17$ and $b = 0.13$ for constant wind.

Table 1 indicates a systematic increase in the coefficient $a$ with increasing $V_L$ and to a lesser extent in $b$. A better fit could be obtained with other exponents than $1/2$ and $1/3$, respectively.
All the experimental waves for a travelling wind field exceed the prediction for a stationary wind field. The bound determined by storm duration $t$ for stationary wind is definitely not a limitation in our test when duration is assumed equal to travel time. The bound determined by fetch is closer to but still below our observations for fetch equal to travel distance.

CONCLUSIONS

The most important result of the study is probably the interest it has stirred up on the subject of polar lows. This interest can be detected on many levels from the theoretical to the practical routine of daily forecasting. A higher awareness of the threat of this particular type of storm is created outside the ranks of meteorologists. The meteorologists themselves have been given an opportunity to increase their own knowledge on the climatology and to sharpen their forecasting tools.

ACKNOWLEDGEMENT

The wave experiment reported here was made possible by a very cooperative staff at the Ship and Ocean Laboratory, MARINTEK, Trondheim. A liberal policy of publishing pursued by the Steering Committee is appreciated.
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1986-04-21-TC/AS-"tc-poac paper 86"
SOME MECHANISMS OF LOCALIZED FRACTURE OF ICE COVER UNDER THE ACTION OF COMPRESSION

Abstract

Investigation is made on compression cracks, a quasi-brittle localized fracture of thin transversally constrained compressed plates. Their characteristics of limiting equilibrium (hummocking toughness) are obtained experimentally for ice and paraffin. Fracture models are considered for tip zones of compression cracks, the latter are regarded as the initiation of hummocking of a solid ice cover.

1 INTRODUCTION

As a further development of the approach suggested by the authors /1, 2/ for the ice cover fracture analysis, the paper considers fracture mechanisms of thin plates subjected to compressive loads in the plate plane under the conditions of constrained transversal displacement /3/. The defined forms of fracture are investigated by way of dividing the problem of deformation of a plate with a source of fracture into an inner problem and an outer one.

Main concepts underlying the paper are based on the fact, ascertained experimentally by the authors, that the quasi-brittle fracture of compressed large and
thin plates of some materials (ice included) on an elastic foundation is strictly localized. The fracture source emerges in the vicinity of the compressive stress concentrator (a narrow notch) and propagates in the form of an elongated fracture zone much narrower than its length, while its surfaces may partially overlap. The fracture products are displaced out of the plate plane. By analogy with normal tension cracks /5/ the present type of fracture is termed "a compression crack". It was observed in the tests that the zone of localized fracture at a compressive crack tip expands autonomously, hence in terms of the outer problem the limiting equilibrium conditions are not significantly affected by the processes taking place in the tip zones. The outer problem embraces problem on the notch with interacting (including overlapping) surfaces and the condition of the limiting equilibrium is assumed in the form

\[ K_I = K_h \]  

(1)

where \( K_I \) is the stress intensity factor of normal compression at the tip of the compression crack, \( K_h \) its critical value characterizing the plate resistance to compression cracks propagation and earlier referred to as hummock formation resistance of ice cover /1-3/.*

The \( K_h \) value is experimentally definable. It seems that the compression crack growth is a necessary initial phase of various linear deformations in the ice cover, namely bedding and hummocking of compressed ice. Also considered here below are various models of fracture mechanics in the inner problem with para-

* Note that the limiting equilibrium of normal tension cracks is given by \( K_I = K_{IC} \) where \( K_{IC} \) is the fracture toughness of the material /5/.
metrical assessment of $K_n$ values.

2 COMPRESSION CRACKS IN THIN PLATES

2.1 Test procedure

The main tests were performed with thin plates of commercial paraffin and type A-4 freshwater ice /4/. Samples in the form of rectangular plate with a side ratio of 2 to 1, were made as large as possible in order to avoid tensile break-down in the marginal parts resulting from tensile stress due to the notched sample bending under the load in the plate plane.* The sample thickness was of the order of 0.01 of its width. The notch was made in the middle of the wider side with a curvature radius of the order of $0.1-1$ mm. For the sake of a better contact with the puncheons the edges under load were strengthened with paper.

The tests were carried out in a special apparatus confining transversal displacement of the samples. The elastic foundation was simulated by substituting one of the apparatus confining walls with a block of porolon (with the elastic foundation coefficient $k$ of about $0.5$ kgf cm$^{-3}$).

2.2 Qualitative interpretation of fracture

According to the reported data on compression tests

* In case of a constant relative length of the notch the stress intensity factor $K_I$ increases along with the increase of absolute values of the sample dimensions ($b_i$);

$K_I = \sqrt{b_i} \cdot q$ whereas the tensile stress in the margins remains a constant. Here $q$ denotes puncheon pressure.
of indented plates there occurs growth of compression cracks and in the immediate vicinity of the compression crack tips (in the tip regions) the local fracture mechanisms of the plate material varies greatly in function of the plate width, material properties as well as the loading rate and confining conditions.

The defined patterns of fracture mechanisms are characterized by initial local cleavage or a combination of ruptures and cleavage as well as a local loss of the plate stability in the tip zone. In all the performed tests the compression crack propagated in a direction transversal to the main compressive stress. Let us consider some principal types of fracture.

The fracture without local loss of stability at a temperature of +18°C and loading rate $K > 10 \text{ kgf/cm}^{3/2}$ in a paraffin plate results in the formation of one cleavage plane that makes an angle of $\sim 45^\circ$ with the plate plane (Fig. 1.1). The cleavage zone typical

Fig. 1. Structure of the compression crack tip.
thickness is $\Delta \approx 0.3$ mm (one or two times larger than a paraffin grain). As the compression crack propagates, its surfaces slide in the cleavage plane and out of the plate plane overlapping each other. The tip zone remains constant in morphology and cleavage geometry irrespective of the sample width (ranging from 0.2 to 8 mm) or compression crack length (up to 100 mm) and that of the initial notch (up to 30 mm). Fracture behaviour on the cleavage contour may be described as a successive tearing-off of paraffin grains under the strain of the longitudinal shear type.

In some loading configurations (inclined and transversal central notch in a plate, one-sided edge notch, etc.) in various phases of growth, compression cracks appear along with normal tension cracks. They interact in propagating and merge under unstable conditions.

The freshwater ice fracture test under similar conditions at a temperature of $t \approx -10^\circ C$ is performed in two steps. First at the notch tip appear several tension cracks oriented transversally to the notch with a length of around that of the sample thickness (Fig. 1.2). Then in the formed blocks cracks of smaller scale develop in the plate plane (Fig. 1.2a) and a cleavage source emerges. After these events the fracture zone expands through the sample under dynamic conditions.

At higher temperatures (or at lower loading rates) a monoclinal fold of non-elastically deformed material develops, with following ruptures at the fold hinges. The ultimate break of the fracture area runs along the rupture lines, after that the cycle starts again.
In the case of sea (salinity of about 2-5\%) columnar ice (type B-4 /4/) with a transversal grain orientation as regards the plate plane, the first step includes the formation of systematic ruptures around the notch. With samples 3-5 mm thick the transversal dimension of the area covered with fractures exceeds 100-120 mm. As the deformation process goes on the ice structure becomes loose in between the systematic ruptures and the ice is forces out of the plate plane.

Thin paraffin plates on an elastic foundation (poly-lon) locally buckle ahead of the notch thus forming a fragment of the stability loss fold. Bending stresses on the fold crest and later in its margins, develop normal tension cracks or those of cleavage (Fig. 1.3). Along the crack lines the plate breaks up by pieces and the area of stability loss expands inward. The plate pieces build up an unstable structure which resembles a "house of cards". Constant dimensions of the stability loss fold fragments are accounted for by the autonomy of the tip zone in the quasi-static growth of compression cracks.

Thin (around 30-50 mm) young sea ice fails in a similar way when compressed. The compression crack tip zone is an autonomously moving fragment of an isolated fold of stability loss recurrently fractured with appearing crack of normal tension.

* The experiment setup did not allow to study this phase of fracture behaviour up to the end.
** Observations of the sea ice compression fracturing were carried out by the authors during their trip on board the ice-breaker in the spring of 1981.
2.3 Hummocking toughness

The compression crack approach in the outer problem helps to obtain the stress intensity factor (hummocking toughness) $K_h$ from values of loads $P$ recorded in quasi-static growth of compression cracks.

In most tests geometrical dimensions of the samples are close to those admitted in fracture mechanics studies for determination of the fracture toughness ($K_{Ic}$), so the $K_h$ value is calculated on the basis of $K$-calibration of these samples /6/.

In the fracture of ice plates no interaction of the slit surfaces is observed. The $K_h$ value is obtained from

$$K_h = Y \frac{P l^{1/2}}{h b}$$

where $b$ is the sample width,
$h$ the sample thickness,
$l$ the length of a compression crack,
$Y$ a calibration factor /6/.

The same formula is used to define $K_h$ for paraffin samples with stability loss. Due to the dynamic nature of compression crack propagation in the ice, the $K_h$ value is assessed for the instant of appearance of fracture pre-structure ($K_{ho}$) and for the instant of onset of cracking activity ($K_h$). The calculated values are given in the table. For the sake of comparison the table also includes values of fracture toughness $K_{Ic}$ for the ice. In the case of paraffin (without stability loss) the interaction of crack surfaces overlapping in the plane of cleavage is taken into account in the form of an effective counter-stress constant through the contact length ($Q$). The calculation is based on the assumption that the effect of the boundaries of a sample with a notch
and a small crack for P and Q loads is embodied by the same calibration term (Y).

\[ K_h = Y \left( \frac{P l^{\frac{3}{2}}}{h b} - \frac{Q (l-l_c)}{h^{\frac{3}{2}}} \right) \]  

(3)

Here \( l_0 \) is the notch length.

\( K_h \) and \( Q \) are simultaneously assessed on the basis of \( P \) force measurement data for cracks of various length in the same sample.

<table>
<thead>
<tr>
<th>Ice type</th>
<th>t°C</th>
<th>( K_{ho} ) (kgf cm(^{-3/2}))</th>
<th>( K_h ) (kgf cm(^{-3/2}))</th>
<th>( K_{lc} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>A - 4</td>
<td>-10 +13</td>
<td>150±40</td>
<td>200±50</td>
<td>18±5</td>
</tr>
<tr>
<td>A - 4</td>
<td>-5 +9</td>
<td>130±30</td>
<td>180±40</td>
<td>12±3</td>
</tr>
<tr>
<td>B - 4</td>
<td>-5 +9</td>
<td>~70</td>
<td>~100</td>
<td>8±3</td>
</tr>
</tbody>
</table>

Table. Hummocking toughness of ice.

Hummocking toughness of the tested materials have proved to be much higher than their fracture toughness.* The value in paraffin samples increases with thickness (Fig.2) whilst the value \( Q \) remains basically unchanged (~3 kgf cm\(^{-2}\)). The latter gives ground to the pattern of effective friction of the crack interacting surfaces adopted for small compression cracks in formula (3). Fracture with a local loss of stability softens the hummocking strength of thin loaded plates (Fig. 2.2).

3 DISCUSSION OF THE OBTAINED DATA

3.1 Fracture without loss of stability

The reported peculiarities of the tested materials as

* Fracture toughness of paraffin \( K_{lc} \) at t°C ~ 18°C amounts to ~4 kgf cm\(^{-3/2}\).
Fig. 2 Hummocking toughness of paraffin.

1-3 equations (4), (14), (16)

\( G_c = 35 \text{ kg cm}^{-2}, \ G_f = 20 \text{ kg cm}^{-2}, \ E = 2 \times 10^3 \text{ kg cm}^{-2} \)

Experiments:

\( \mathcal{I} \) - without a local loss of stability,

\( \mathcal{I} \) - with a local loss of stability.

regards their fracture mechanics in compression crack tip zones provide a sound basis for developing compression crack models in terms of the inner problem and estimation of the hummocking toughness using parameters of the observed fracture behaviour.

In paraffin the compression crack tip zone is formed by the cleavage area. Let us assume that the dimensions of the compression crack tip zone (in the plan view) are roughly equal to the projection of the cleavage front to the plate plane and, the cleavage angle being constant, proportional to the plate thickness. At the onset of crack growth the tip zone contour element is subjected to a stress characterizing its strength. If the characteristic stresses at the tip zone contour are supposed to be constant in a state of limiting equilibrium, a fracture model, similar to the concept of plastic zone in fracture mechanics, may be developed /5/. Its parameters are
related in the form of

\[ K_c = c \sigma^* r^{1/2} \]  \hspace{1cm} (4)

where \( K_c \) is the critical value of the stress intensity factor,

\[ c = (2\pi)^{1/2} \]

for a plane stress state,

\[ r \] the radius of the plastic zone.

Equation (4) gives a good fit for the test data (Fig. 2, curve 1) and with \( r = h/2, K_c = K_h, \sigma^* = 35 \text{ kgf cm}^{-2} \) (\( \sigma^* = 30 \pm 5 \text{ kgf cm}^{-2} \) is the paraffin strength in uniaxial compression).

Let us assess the fracture parameters on a smaller scale. A unit area of the cleavage front consists of a mode III /5/ crack. To evaluate the material fracture toughness mode III \( K_{IIIC} \) from the \( K_h \) value it is assumed that energy consumption in the compression crack tip zone is the sum of energies absorbed in shear cracks in every unit layer of the plate material (its thickness being of the order of the cleavage zone thickness \( \Delta \) (Section 2.2)). Also taking into account that the cleavage makes an angle of 45° to the compression plane we get

\[ K_{IIIC}^2 \sim (K_h \cos \frac{\pi}{4})^2 \cdot \frac{\Delta}{h} \]  \hspace{1cm} (5)

For paraffin \( \Delta \approx 0.3 \text{ mm} \), hence \( K_{IIIC} = 8 \text{ kgf cm}^{-3/2} \). It is assumed here\(^*\) that unlike shear of plastic material failure /7/, the critical state of the cleavage front under compression is defined basically by the \( K_{II} \) value.

The shear angle can be estimated on the assumption that under the stated terms the energy distribution

\(^*\) The model in question may be extended to other types of brittle grain media.
of the elastically deformed plate with growth of compression cracks \( (\partial W/\partial \ell) \) is equal to that of the effective energy of cleavage surface (T).

\[
(6) \quad \frac{\partial W}{\partial \ell} = \frac{2 T}{\sin \alpha}
\]

where \( \alpha \) is the cleavage angle.

From Irwin's equation /5/

\[
(7) \quad \frac{\partial W}{\partial \ell} = \frac{n K_h^2}{E}; \quad 2 T = \frac{(1+\mu)}{E} K_h^2 c
\]

\( n = (1-\nu) \) is the plane strain,
\( n = 1 \) - the plane stress state.

From (6) and (7) with \( K_h c \sim K_h \cos \alpha \) for a unit layer and \( \mu \sim 0.3 \) we get \( \alpha \approx 43.4^\circ \) a plane stress state, \( \alpha \approx 45.2^\circ \) a plane strain (note that in the experiment \( \alpha \approx 45^\circ \)).

From visual observations the cleavage micromechanics in a grain medium (paraffin) involves successive tearing-off of separate grains. Understandably it is initiated due to the excess of shear stresses, under the conditions of anti-plane strain, on the continuation of the crack mode III oriented at an angle of about 45° to the compression plane.

It should be noted that the shear stress maximum orientation remains unchanged including the case of a successive tearing-off (formation of voids) in an elastic plate at anti-plane strains.

The model of a compression crack tip zone in fresh-water ice should contain a more complex fracture morphology (see Section 2.2). In the first phase of fracture emerges successively a structure of transversal ruptures (note that in the case of ice the appearance of ruptures is characteristic of the fracture behaviour in compression /8/). Their transversal orientation is accounted for by the fact that at plane strain
conditions the compressive stress $\sigma_{zz}/5$ (across the plate) arresting ruptures, within angles of $\theta \sim 45^\circ + 90^\circ$ counting off from the notch continuation, is greater than $\sigma_{xx}$ (along the crack). Further loading complement the series of transversal ruptures with that of fractures in the plate plane. They are seemingly associated with the fact that at the rizen level of stress $\sigma_{yy}$ the $\sigma_{zz}$ stress is unable to arrest rupture activity.* The formation of fractures at a new level resulting in the plate splitting within the already appeared blocks, enhance the possibility of a macrocrack in the deformed area and its failure.** Then the process re-occurs.

Principal stresses $\sigma_{1,2}$ in the plate plane and in the immediate vicinity of the notch tip are defined as /5/

$$\sigma_{1,2} = \frac{K_I}{(2\pi r)^{1/2}} \left( \cos \frac{\theta}{2} + \sin \frac{\theta}{2} \left(1 - \cos^2 \frac{3}{2} \theta \right) \right)$$

where $r$ is a small distance to the notch tip.

Assuming that the appearance of first transversal ruptures indicates that in a given area $(r \sim h)$ the stresses attain a level corresponding to the ice

---

* Strictly speaking, the analysis of this phase of fracture should take into account the whole set of ruptures, however, a quantitative assessment may be accomplished on the assumption that small ruptures exert but slight effect on the stress field at the notch tip.

** In more elastic-brittle materials with rigidly confined transversal displacement of the plate may develop a hierarchy of fractures with a variety of scales of diminishing jointings, indispensable in the creation of instability of the system under strain through the compression crack tip zone on the whole.
strength in compression tests $\sigma_c^*$ /8/ with the principal stresses calculated from equation (8), we can estimate the hummocking toughness at the beginning of the structure of fracture formation in the tip zone of laboratory samples. In the test, first cracks were observed at $\theta \sim 70^\circ$. This angle is defined by $\theta \sim 5.7$, with (8) we get

$$K_h \approx c \cdot \sigma_c^* \left(2^{\frac{1}{2}} h\right)^{\frac{1}{2}}; \quad c \sim 1.5$$

(9)

The $K_{ho}$ values from (9) check well with experimental data ($K_{ho} \sim 150$ kgf cm$^{-3/2}$ for $h \sim 0.3$ cm, $\sigma_c^* \sim 80$ kgf cm$^{-2}$) and evaluate $K_h$ from below.

Determination of $K_h$ for the ice cover of an actual-situation thickness requires a difficult operation. It may be shown, however, that if at least in general the fracture behaviour of the ice in the tip zone remains the same, $K_h$ is not likely to rise considerably with an increase of thickness due to the scale effect of ice strength. From /8/, for example,

$$\sigma_c(h) \sim \sigma_c^0 \cdot \left(\frac{h_s}{h}\right)^{\frac{1}{2}}$$

Here the (0) index refers to samples of small size. From this term and (9) we obtain

$$K_h \sim \sigma_c h^{\frac{1}{2}} \sim \text{const}$$

3.1.2 Fracture at loss of stability in the tip zone

Let us consider two extreme situations of fracture in the tip zone.

Case 1. The plate thickness is small. The fracture events at the plate bending are remote from the buckling front after loss of stability.
Case 2. The plate thickness is larger (close to the limit*), the material strength is thus exhausted at the front of local loss of stability.**

Now let us apply a model of compression crack tip zone similar to Dugdale's /5/ to Case 1. The undeformed part of the stability loss fold is assumed to be a narrow strip with an average stress ($\sigma_{yy}^{*}$), normal to the fold axis in the plate plane, is a constant. The stresses are inferred from the term of elastic loss of stability of the tip zone fragment as the rod on an elastic foundation.

$$\sigma_{yy}^{*} \approx \frac{1}{\sqrt{3}} (E \Delta k)^{\frac{1}{2}}$$

(10)

Fracture condition is used in the form of

$$\sigma_{\text{max}} = \sigma^{*}$$

(11)

where $\sigma_{\text{max}}$ is the maximal stress in the bended plate, $\sigma^{*}$ the plate material strength.

The $\sigma_{\text{max}}$ value can be obtained from elastic equilibrium of the fold element. The latter will be simulated with a bar of unit width and $H$ length (semi-wave of stability loss of a bar on elastic foundation), loaded at edges with a concentrated force $F = \sigma_{yy}^{*} \cdot h$.

From this term and (11) we obtain

$$|\sigma^{*}| = \frac{6M_{f}}{h^2} \pm \sigma_{yy}^{*}$$

(12)

* For paraffin on porolon foundation the maximum thickness at which loss of stability in the tip zone may occur, is about 3 mm. Corresponding estimates for a floating ice cover give $\sim 0.3-0.5$ m.

** The estimates of Case 2 give thus the lower limit of hummocking toughness values.
where $M_4$ is the bending moment at the fold hinge, the sign "+" corresponds to compression, the sign "−" to tension. Critical opening of the crack in Dugdale's model is associated with the utmost displacement of the fold margin at elastic bending at the instant when the fracture conditions are satisfied. For small deflections the fold margins longitudinal displacements ($\delta_y$) are related to the transversal displacements of its middle part ($\delta_z$), from the model of a width-unit bar, in the form of

$$\delta_y \approx \frac{T^2}{2} \cdot \frac{\delta_z}{H}, \quad H \approx \pi \left(\frac{E h^3}{12 k}\right)^{\frac{1}{4}} \quad (13)$$

From these terms and (10-12), making use of the relationship between $\delta_y$ and $K_c$ in Dugdale's model, we finally obtain

$$K_h \approx (\delta_y \cdot \sigma^* \cdot E)^{\frac{1}{2}} \quad c \cdot E \frac{V}{(k h)^{\frac{1}{2}}} \left(\frac{\sqrt{2} \cdot |\sigma^*|}{(E k)^{\frac{1}{2}}} + h^{\frac{1}{2}}\right) \quad (14)$$

The signs "−+" correspond to the fracture condition on the compressed and tensile-stressed sides of the plate respectively.

For thicker plates (Case 2) it should be taken into account that the final fracture involves the hinge of the stability loss fold as well as its margins, thus the effective width of the compression crack tip zone (width of fracture zone) is roughly equal to the stability loss fold width. So the buckling (and failing) plate fragment at the compression crack tip is of constant transversal sizes, while its contour, from experimental observations, is convex and smooth. It will be modelled in the form of a semicircular notch of constant curvature radius. It should be noted that if a thin plate with a notch is tensile-stressed, the emerging compression stresses on its contour lead to loss of stability, the critical conditions of which are defined by /9/:
\[ P_c \approx c E \left( \frac{h}{R} \right)^2 \quad ; \quad c \sim 0.1 \]

where \( R \) is the notch radius.

Extending this concept to the plate compression and assuming that at least for the loss of stability in the contour zone the \((C)\) value is proportional to the stress concentration factor, with \( R \sim H \) we obtain

\[ K_h \sim m k \frac{3/6}{s/6} E^{3/6} h^{3/6} \quad ; \quad m \sim 1 \]

If compared, the terms (14, 16) and the experiment data for paraffin (Fig. 2) are in good qualitative agreement. The corresponding calculations for an ice cover are given in Fig. 3. In the region of small cracks of the plate, the loss-of-stability phenomenon softens notably the effective hummocking toughness of materials. Also observed is a certain strengthening effect if the fold is longer and the plate thickness is very small (Case 1). It is observed that in the region of fracture mechanisms change (with plates extremely thick), the abrupt change of inner

![Fig. 3 Calculations of the hummocking toughness of ice with a local loss of stability.](image-url)
problem scale (tip zone) entails the possibility of transitional fracture behaviours sensitive, for example, to the parameters of initiating disturbances.
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Impact Forces and Friction Coefficient on the Forebody of the German Polar Research Vessel "POLARSTERN"

1. Introduction

The icebreaking capability of ships is strongly influenced by the friction between the ice and the hull. Although this fact is discussed very often in literature, measurements of the friction coefficient between ship's hull and ice have not been carried out in full scale.

Even though the actual friction coefficient in nature is more or less unknown, it has to be simulated in model tests. In addition measurements in laboratories can not take into account important parameters like snow coverage on the ice, water between ship's hull and ice, the influence of the normal force and the influences of ice, water and hull temperatures.

The knowledge of impact forces on ships in ice is also limited. But it is of great interest to the ship construction because some results of impact tests with ships against multiyear ice indicated higher impact forces than classification societies had assumed [1]. The knowledge of the impact forces in various kinds of ice is important for the safety of ships in ice.

In order to gain more knowledge on both problems HSVA has performed measurements of normal and tangential forces induced by ice on the hull of the German polar research vessel "POLARSTERN" in May 1984.
2. Measuring Equipment

In the forebody of the "POLARSTERN" (on the starboard side) two triaxial force measuring devices have been installed in pockets at the waterline 10. The front device is located between frames 110 and 112, the other in the shoulder of the forebody between frames 100 and 102. Fig. 1 shows the position of the two force measuring devices.

Each force measuring device has been equipped with four triaxial load cells. The load cells are connected to the bottom of the pockets, the top supports a plate (of about 1.4 m x 0.8 m) which is even with the outer shell of the hull. In Fig. 2 the load cell arrangement is schematically displayed.

The surface of the plates has been coated with INERTA 160, a low friction and durable coating. But the temperatures at the time of coating (April 1984) did not satisfy the required conditions.

The signals produced by the four load cells of each pocket are added with respect to their directions, amplified, digitized with a rate of 50 Hz per channel and recorded on a digital cassette tape recorder with high enough recording frequency to store the data on line. Fig. 3 shows an example of a time series for the two tangential forces and the normal force.
Fig. 1: Position of the Pockets on the "POLARSTERN"

Fig. 2: Cross Section of one Pocket

Fig. 3: Example of Time series
3. Analysis

The friction coefficient $\mu_F$ is defined as the ratio of tangential force $F_t$ and the normal force $F_n$. The friction coefficient may be effected by the velocity $v$, the normal force $F_n$ and the mean pressure $P$ on the area of contact.

$$\mu_F(v,F_n,P) = \frac{F_t}{F_n}$$  \hspace{1cm} (1)

Because the tangential forces had to be measured in two directions, the resultant force has to be computed before.

$$F_t = \sqrt{(F_{tv}^2 + F_{th}^2)}$$  \hspace{1cm} (2)

In order to get the frequency distribution of the normal and tangential forces of each test they have been classified. An example of the results is shown in the Figs. 4, 5 and 6, for normal forces and the two tangential forces of the front load measuring pocket. It shows the forces when "POLARSTERN" navigated in pack ice.

The frequency distributions of each single test have been summed up to get total results for the whole measuring time as well as to get results for each different ice condition. Hereby, the classes started at a normal force of zero with intervals of $F = 100$ kN. All forces below $F_n = 10$ kN have been suppressed in order to eliminate the influence of zero drifting of the amplifiers and the temperature drifting of the strain gauges at low forces. The friction coefficient has been calculated for each sample and co-ordinated to the normal force.
Fig. 4: Frequency Distribution of Test No 4258

Fig. 5: Frequency Distribution of Test No 4258

Fig. 6: Frequency Distribution of Test No 4258
4. Results

4.1 General

Measurements have been performed under the following different conditions:

- in level ice with different ice thicknesses in the range between 0.7 m and 1.5 m. The flexural strength varied from 250 kPa to 350 kPa
- in pack ice and broken ice with different degrees of coverage
- in ramming of multiyear ice floes
- in the self broken channel of the ship
- in manoeuvring tests.

4.2 Normal forces and ice load on the hull

The mean values and the values of 98%-limits of the normal forces of both pockets are presented in Table 1.

The frequency distribution of the normal force of the shoulder pocket in level ice is presented in Fig. 7. The mean values and the 98%-values of normal forces of the front pocket under this ice condition are the highest of all ice conditions. The reason of this behavior may be the steady state of breaking ice and the steady touching of floes on the hull. The highest value of normal force was measured with $F_n = 2800$ kN.

Similar to the results in level ice were those in pack ice and ice floes, which are presented in the Fig. 8.
The smallest mean normal forces have been obtained from measurements when the ship moved in her own broken channel and from manoeuvring tests. The highest impact load occurred during the rammings with multiyear icefloes. The load of the impact in one case was so large, that one of load cell in the shoulder pocket was destroyed. The rise time of this impact was so short, that any statement about the force is impossible. It is only known, that the load cell has the capability for measuring forces in normal direction up to 4000 kN and the area of impact exerted on this load cell is less the 0.5 m².

The frequency distribution of the normal forces for whole measuring time for both pockets are plotted in Figs. 9 and 10. Table 2 shows the distribution of the normal forces as absolute numbers of the samples and relative frequencies as functions of the normal force.

---

<table>
<thead>
<tr>
<th>Ice Condition</th>
<th>Normal force [kN] Front pocket</th>
<th>Normal force [kN] Shoulder pocket</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean value</td>
<td>90%-value</td>
</tr>
<tr>
<td>Level Ice</td>
<td>306</td>
<td>1500</td>
</tr>
<tr>
<td>Broken channel</td>
<td>141</td>
<td>600</td>
</tr>
<tr>
<td>Manoeuvring tests</td>
<td>306</td>
<td>800</td>
</tr>
<tr>
<td>Pack ice</td>
<td>270</td>
<td>1000</td>
</tr>
<tr>
<td>Ice floes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Raming of Floes</td>
<td>299</td>
<td>1100</td>
</tr>
<tr>
<td>Total</td>
<td>302</td>
<td>1000</td>
</tr>
</tbody>
</table>

Table 1: Normal Forces at different Ice Conditions
Fig. 7: Level Ice

Fig. 8: Pack Ice and Ice Floes

<table>
<thead>
<tr>
<th>Normal Force [kN]</th>
<th>Front Pocket</th>
<th>Shoulder Pocket</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>797</td>
<td>90.99</td>
</tr>
<tr>
<td>120</td>
<td>526</td>
<td>99.34</td>
</tr>
<tr>
<td>130</td>
<td>359</td>
<td>99.80</td>
</tr>
<tr>
<td>140</td>
<td>228</td>
<td>99.73</td>
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<td>150</td>
<td>242</td>
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<td>160</td>
<td>82</td>
<td>99.95</td>
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<tr>
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<td>19</td>
<td>99.96</td>
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<td>99.46</td>
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<td>0</td>
<td>100.00</td>
</tr>
<tr>
<td>280</td>
<td>1</td>
<td>100.00</td>
</tr>
</tbody>
</table>

Table 2: Number of Samples, Relative and Cumulative Frequency and Friction Coefficient at both Pockets vs. Normal Force Total Results
4.3 Friction Coefficient

Coulomb's friction theory based on the assumption that the friction coefficient is independent of the normal force, mean pressure at the contact area and the velocity between both surfaces.

The results of the "POLARSTERN"-measurement - given in Tables 2 and 3 and Figs. 11 to 14 - show under all ice conditions a totally different picture: a significant influence of normal force on the friction coefficient. In these figures it is evident that the friction coefficient decreases from approx. 0.25 to approx. 0.08 when the normal force increase up to approx. 1500 kn. Then the friction coefficient seems to increase with the normal force, but this conclusion should used very carefully since only a small number of samples are available in this range. Fig. 15 shows the absolute number of samples for the normal force classes at the shoulder pocket.
<table>
<thead>
<tr>
<th>Ice Condition</th>
<th>Front pocket Mean value</th>
<th>Shoulder pocket Mean value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level ice</td>
<td>0.164</td>
<td>0.171</td>
</tr>
<tr>
<td>Broken channel</td>
<td>0.224</td>
<td>0.206</td>
</tr>
<tr>
<td>Maneuvering tests</td>
<td>0.187</td>
<td>0.176</td>
</tr>
<tr>
<td>Pack ice</td>
<td>0.128</td>
<td>0.146</td>
</tr>
<tr>
<td>Ice flows</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ramming of Floes</td>
<td>0.191</td>
<td>0.253</td>
</tr>
<tr>
<td>Total</td>
<td>0.139</td>
<td>0.166</td>
</tr>
</tbody>
</table>

Table 3: Friction Coefficient at different Ice Conditions

Fig. 11: Level Ice
Fig. 12: Pack Ice and Ice Floes
Fig. 13: Total Results

Fig. 14: Total Results

Fig. 15: Number of Samples vs. Class of Normal force
Similar results have been obtained by Forland and Tattinclaux [2], but the measuring method, the range of normal force and the friction coefficient are different.

The effect of the surface pressure could not be determined in these tests. Although the size of the surface of each pocket is well known, it has to be realized, that real area of contact between ice and surface of the pocket is less than or equal to the surface area of the load measuring pockets. So all calculations of the surface pressure can produce only minimal values of pressure.

The influence of the velocity between ice and surface is displayed in the Fig. 16. Speed measurements have been performed only during the level ice tests. Therefore all given information refers to this ice condition. The real local differential speed between ship’s surface and ice could not be measured, therefore, as a first approximation, ship’s speed has been used instead.

![Fig. 16: Friction Coefficient vs. Ship Speed in Level Ice Front and Shoulder Pocket](image-url)
The results of both force measuring pockets are different. At the shoulder pocket the friction coefficient increases with the ship speed nearly linearly. The correlation between friction coefficient and speed at the front pocket shows more or less an independence of the friction coefficient from the speed. Whether the reason for this behavior is caused by the influence of the unknown local speed or by the influence of normal force can not be determined.

The last parameter that is to be discussed, is the change in the quality of the surface of the measuring plates. Due to the improper coating conditions in the shipyard the coating material slowly broke off from the connection to the steel surface. So at the end of the tests only small areas of the surface were still covered with the coating material.

5. Conclusions

At normal first year ice conditions (level ice, ridges, broken ice cover) forces induced by ice contact with the hull at the waterline of the "POLARSTERN" have been less than 2800 kN. Ramming of large multiyear ice floes can produce unpredictable high forces, especially at higher ship speeds.

Friction coefficient has been determined by dividing the measured normal and tangential forces. The friction coefficient was found to be dependent on the normal force and not independently from speed.

Further tests on ice impact forces and measurements of the friction coefficient have been carried out in May 1985 around Spitzbergen in first and multiyear ice. The results, which are presently being analyzed, are expected to answer some of the questions which remain open in this paper.
6. References


MEASUREMENTS AND ANALYSIS OF ICE FORCE AGAINST A CONICAL OFFSHORE STRUCTURE

Abstract

A Finnish joint project, led by the Department of Mechanical Engineering at the University of Oulu, has started to research the loads that moving ice exerts on a conical offshore structure. To obtain full scale ice force data, an instrumented test cone was mounted around the Kemi I lighthouse in the northernmost part of the Gulf of Bothnia. Ice movement was exceptionally pronounced throughout last winter and several tens of hours of data were recorded. The ice features encountered by the cone include level ice 5 to 70 cm in thickness, rafted ice and pressure ridges of different sizes. As only rough preliminary results were available, more attention is paid here to model tests with cones and to ice failure patterns.

Model tests for the Kemi-I cone have been conducted in the scales of 1:30 and 1:15. In addition, small scale tests have been performed with cones of different slope angles. The model test results have been compared with the results of the force calculation method based on the plasticity theory. The correspondence between the results of the model and full-scale tests is discussed. In full scale, crushing failure was observed at times in level ice, but this mode never predominated in model scale.

*) The author was employed during this research by the University of Oulu, Department of Mechanical Engineering, Oulu, Finland
1 INTRODUCTION

In the spring of 1983, a cooperative project was started in Finland for researching the ice forces exerted against a conical offshore structure in full scale. The University of Oulu assumed responsibility for the project, in which the largest Finnish shipyards, construction companies and state research organisations took part. Almost half of the financing came from the Ministry of Trade and Industry.

The chief advantage of a cone over a vertical structure in ice-infested waters is the icebreaking mode. In failure by bending, the ice forces are smaller than in failure by crushing against a structure of the same breadth at the waterline. In addition, the vertical component of the ice force acting on the cone increases the stability of a gravity structure, if the cone deflects the ice upwards. If the ice is deflected downwards, the effect is the opposite, but the ice force is smaller. In the case of pressure ridges a cone will not be better than a vertical structure, unless the main force component is caused by thick level ice layers inside the ridge, which the cone breaks by bending instead of crushing.

Several models have been developed for calculating the forces that ice exerts on a conical structure. For level ice, the basis has been the elasticity or plasticity theories, but for ice ridges the principles of soil mechanics have usually been applied. To verify the calculating methods, a fairly large number of small-scale model experiments have been performed.

To ascertain whether the theories or scaling laws hold true in full scale, a full-scale structure is needed. For ships full-scale ice resistance measurements have been performed for a long time, and the correlation between full and model scales for ship hulls of different shapes is fairly well known. As regards offshore structures, especially cones, some lighthouses exist, but none of them has been instrumented to show the total ice load. The cone at Kemi I serves as a full-scale test object for sub-arctic seas and a very large model for real arctic conditions.
A cone consisting of a steel sandwich shell with a concrete filling has been assembled around the Kemi I lighthouse. The angle of slope of the cone is 55° from the horizontal and the diameter at the mean water level is 10 m. The cone is supported, in principle, in such a way that all the forces transmitted from the cone to the lighthouse and to the caisson can be determined, Fig. 1. The cone rests on the caisson of the lighthouse on rubber pillows, the deformations of which are measured. In the gap between the lighthouse shaft and the upper part of the cone are rubber bags filled with alcohol mixture. The horizontal forces transmitted by the bags are obtained directly from pressure fluctuations of the liquid in the bags.

Another system for determining the horizontal force is rods inside the lighthouse structure for measuring bending deformations of the lower part of the lighthouse. These transducers were installed for measurements of the ice force exerted against a vertical structure /1/. Moreover, there are 80 strain gauges glued in the cone shell. A FEM model of the structure is then applied to determine the distribution of ice force from the measured strains. The vibrations of the lighthouse shaft are measured with acceleration transducers. The structure and instrumentation of the cone are described in more detail in /2/.

The Kemi I lighthouse is situated in the northernmost part of the Gulf of Bothnia, about 40 km off shore, in the region of active ice movement. Last winter the level ice occurring by the lighthouse had a maximum thickness of 0.7 m. The water depth at the site is 12 m and the ice ridges sometimes extend to the sea bottom. The water salinity is 0.6-0.8 % and the sea is ice-covered from December to the end of May.
Fig. 1: Kemi-I lighthouse with icebreaking cone.

Fig. 2: Slow level ice movement.
2.1 Measurements

The ice movement was exceptionally pronounced throughout the winter of 1985. The ice features encountered included level ice up to 0.7 m thick, rafted ice and small and medium-sized pressure ridges. The ice velocity varied from almost zero creeping speed to over 0.2 m/s. There was no prevailing direction of ice movement. The ice field can stop and after a while start to move in any direction or the ice can change its course slowly and smoothly. In addition to wind, sea currents exert driving forces on the ice. These currents are generated by fluctuations in the sea level caused by air pressure changes in the region of the Baltic Sea.

2.1.1 Level ice

In early winter thin level ice (5-20 cm) breaking against the cone formed floating rubble in front of the structure. When a pressure ridge was encountered, the rubble grounded on the caisson. The failing ice started to pile up until the rubble reached a stable quantity. Ice force records were not obtained for the early winter stage, because of some difficulties with the measuring system.

In the case of thicker level ice (30-70 cm), several icebreaking and clearing patterns were observed. If the ice movement was very slow, some metres per hour, the ice behaved in a ductile manner and rode neatly up the cone and the lighthouse wall, Fig. 2.

At greater ice speeds, the ice tended to form rubble in front of the cone. Sometimes the amount of rubble was so great that it reached down to the caisson; sometimes it was smaller. When the rubble had grown sufficiently, the ice failure mode was by crushing, Fig. 3. The ice pieces were small and irregular in shape. There had been flaking and shearing failures, because in many ice pieces the failure planes were parallel and oblique in relation to the ice sheet plane.
Fig. 3: Fast level ice movement.

Fig. 4: Circumferential cracks.
The ice sheet penetrated the rubble and failure evidently occurred against the cone surface. The weight of the ice rubble pressing the ice sheet from above and below acts as a guide, preventing the sheet from bending upwards. As the crushing failure mode was observed only when the ice was snow-covered, it is not possible to say whether primary cracks occurred by bending.

When the amount of rubble in front of the cone was small, the entering ice sheet raised the ice stack and the failure was by bending. Depending on the balance between the weight of the ice rubble on the cone surface and the buoyancy of submerged ice blocks, the failed ice sheet either collapsed or rode up the cone surface. The failed ice pieces were regular in shape and of almost uniform size.

An interesting phenomenon observed in late spring, when there was no snow left on the ice, was double or even triple circumferential cracks. Ice speed was relatively high and the failure mode was by bending. At times circumferential cracks were seen, which opened upwards and were located much farther from the cone than the ordinary crack caused by upward bending. The ice sheet must have failed farther by bending due to the dynamic action of ice sheet. Then the crack by turns opens downwards when the ice becomes wet, and upwards when it dries, and sucks water from the wet slush on top of the ice. At that moment the crack will be observed as a white track in the slush, Fig. 4.

Broken ice rode up on to the top of the cone, gathered at a level of 2.3 m and formed a continuation of the cone. The level ice did not ride up over a level of 4 m, except in the very slow speed condition, when it climbed up to 5 m.
The ice strength tests carried out in the field by WARC consisted of cantilever beam bending tests in-situ and uniaxial compressive strength tests. The flexural strength in upward bending was about 75% of the strength in downward bending. The crushing tests were performed with a portable hydraulic field-testing machine. The strain rate was approximately $4 \cdot 10^{-2} \text{ s}^{-1}$, causing brittle behaviour of the ice. The ice samples included cylinders with a diameter of 100 mm, obtained with an auger, and cubes with sides of 100 mm. The length of the specimens was 240 mm. Samples were taken from the top and bottom parts of the ice sheet in both the horizontal and vertical directions. The crushing strength of the vertical samples was about twice that of the horizontal samples.

2.1.2 Ridges

The ice ridges encountered by the cone were small and mediumsized. They did not reach the sea bottom, but many of them clearly touched the caisson. When a ridge grounded on the caisson, the ice masses started to travel upwards, forming an ice stack, which could be up to 5 m high. Deep ridges are not the best for the purpose of determining the ice load of a pressure ridge against a pure conical structure, because the caisson modifies the shape of the ridge and raises up the whole ice mass.

As the cone penetrated a pressure ridge, there was a strong flow of ice blocks and brash upwards from the inner parts of the ridge. Ice blocks, longer than 3 m and more than 1.5 m thick, were raised up. The blocks consisted of two or three level ice layers frozen together. The level ice following the ridge either penetrated the ice rubble or rode up on it.
3 SMALL-SCALE MODEL TESTS

In conjunction with the full-scale measurements at Kemi I, small-scale experiments have been carried out at the University of Oulu and in the Wärtsilä Arctic Research Centre (WARC).

In Oulu the tests were performed for the Kemi I cone in the scale of 1:30 in a very small ice basin, measuring 1.5 by 1.1 m and with a depth of 0.4 m, Fig. 5. The ice was made in the conventional way, using a 0.8% urea solution. The model was pushed by a displacement-controlled hydraulic jack, equipped with a force transducer. It was found that successful model tests can be performed even in such a small basin. The stroke length of the model was sufficient to attain the steady state condition in most cases.

The ice behaviour was observed to be perhaps too ductile. The ice pieces did not separate properly after the cracks had formed, but were bonded together by the upper layer of ice. Ice pieces rode up high along the cone and the vertical superstructure as if they were hinged together. The flexural strength of the ice when it was bending downwards was 1.5-3 times that when it was bending upwards. This is a consequence of the structure of the ice sheet: a thin layer of stiff ductile ice on the surface and the rest consisting of columnar vertical grains loosely bonded together.

As the contribution of the Wärtsilä Helsinki Shipyard to the cone project, WARC performed model tests for the Kemi I cone in the scale of 1:15. The arrangement of the tests and the results are reported in /2/.
Fig. 5: Model test experiment in the University of Oulu. Cone diameter at waterline 32 cm.

S/05.12.84 Downward breaking cone. Level ice.
Ice speed 20 m/s
Flow strength 50 kPa
Cone angle 85 deg
Cone diameter 32 cm

4/04.12.84 Upward breaking cone. Level ice.
Ice speed 40 m/s
Flow strength 45 kPa
Cone angle 60 deg
Cone diameter 32 cm

Fig. 6: Ice force records. Model tests in WARC.
The University of Oulu, with support from the Finnish Academy, performed model tests with cones having slope angles of 40° and 65° from the horizontal and waterline diameters of 65 cm and 90 cm, respectively. Tests were also performed with a downward-breaking cone with a slope angle of 65° that deflected the ice downwards. The test arrangement was almost the same as for the Kemi I model cone in /2/. The tests included runs in level ice at speeds from 5 to 160 m/s, in rafted ice and in ice rubble. The level ice thickness varied from 40 to 60 mm and the flexural strength from 27 to 50 kPa.

Fig. 6 gives examples of force records. Ice is pushed in the negative x-axis direction, the z-axis is vertical with the positive direction downwards, and the y-axis is perpendicular to both the x-axis and the y-axis. The 40° upward-breaking cone has gradually growing force peaks, which is due to an increasing amount of ride-up ice on the cone surface. In contrast, the downward-breaking cone has almost constant peak forces from the beginning of the run.

The downward-breaking cone had an almost stationary icebreaking and clearing process, but the upward-breaking models had more irregular behaviour. The latter cones gathered varying amounts of ice blocks on their surface, which were then suddenly cleared away by down-humping. In the tests with the 65° upward-breaking cone, considerable crushing of the ice sheet edge occurred, but the final failure was always by bending.

In Fig. 7 the ice forces are plotted against ice speed. The values are plotted without using any correction of the results. If the variation of ice thickness and flexural strength is taken into account, there is still a slight dependence on speed, particularly for the steep cones.
Fig. 7: Ice force vs. ice speed. Model tests in WARC.

Fig. 8: Measured vs. predicted ice forces. Model tests in WARC.
4 COMPARISON WITH THEORY

4.1 Model tests

Here the above-mentioned tests performed in WARC by the University of Oulu are dealt with; the model tests done by Wärtsilä for the Kemi I cone are presented and compared with the theory in /2/.

The small-scale level ice test results have been compared with Ralston's /3/ approach. The model takes into account the formation of radial and circumferential cracks, the bending (or "deforming region") of the ice sheet, the work to raise the ride-up ice, and the friction between the ice and the structure.

In this case the ride-up ice thickness has been reduced to correspond to the amount of ice observed on the cone during the tests. In addition, the portion of the ice load which is caused by the curvature change of the ice plate within the circular crack, i.e. "the deforming region" has been neglected. This can be done because the maximum force occurs at the time of the formation of the circumferential crack, and the radial cracks already exist at that moment. The ice acts as separate radial wedges.

The agreement of the test results with the theory is satisfactory in the case of the upward tapering cones and particularly with horizontal forces (Fig. 8). The modified calculation model seems to underestimate the vertical loads, and the loads exerted on the downward tapering cone. The mean values of the force peaks agree well with the latter cases.

The ice piece size varied from test to test. With the 65° cone that deflected ice upwards, the piece size decreased to about half as the speed increased. This was obviously due to increasing dynamic forces at higher speeds. Gathering of ice blocks in front of the cone was also stronger when the ice speed was increased. The behaviour was much the same as in ice failure by bending with Kemi I.
In the model tests for the Kemi I cone /2/ the ice piece size showed no clear dependence on speed or ice properties. Considerable piece size variation and ice block gathering existed in those tests as well. Sometimes the small piece size was due to secondary failure of the ice. An initially long ice wedge breaks into two pieces when the cone lifts the end of the wedge out of the water. On the whole, the size of the deforming region was too large in most of the model test runs, compared with Ralston's model with a circular circumferential crack.

Sometimes the breaking pattern of the crack was cosine-shaped rather than circular, particularly in the experiments in Oulu. In Fig. 9 the ratio $A/R$ and coefficients $A_1$ and $A_2$ in Ralston's formula /3/ are plotted against the weight:strength ratio $\frac{\rho w g D^2}{\beta_f t}$ for circular and cosine-shaped circumferential cracks. The horizontal ice force component is

$$F_H = \left[ A_1 \beta_f t^2 + A_2 \rho w g t D^2 + A_3 \rho w g t R (D^2 - D_T^2) \right] A_4 \quad (1)$$

in which $\beta_f$ is the flexural strength of the ice, $t$ the level ice thickness, $\rho_w$ the water density, $g$ the gravity acceleration, $D$ the cone diameter at the waterline, $D_T$ the cone top diameter, and $t_R$ the ride-up ice thickness on the cone surface. Coefficients $A_3$ and $A_4$ can be obtained from /3/.

The figure presents both the case in which the "deforming region" is omitted, i.e. when the ice breaks into separate wedges, and the opposite case, in which the circumferential crack is assumed to form before the radial cracks. The Tresca yield criterion is applied, the flexural strength is assumed to be equal in upward and downward bending.

The influence of the crack shape on the total ice load is not as significant as was expected. The ratio $A/R$ in most upward bending tests corresponds better to the $A/R$ of the cosine shape, whereas in the downward bending mode the circular crack shape is more satisfactory.
Fig. 9: Coefficients for Ralston's formula /4/ with different shapes of circumferential crack.

4.2 Full scale

Since the analysis of the measurements from Kemi I was started only recently, just the first rough approximations are available. The measured forces have been of the same order as was expected.

The distance between the circumferential crack and the cone waterline varied with the failure mode. If the failure was due to pure upward bending, and no accumulation of ice blocks occurred, the distance corresponded well with the calculation using Ralston's model with a circular crack. In the case of downward bending failure caused by the weight of ride-up ice, the location of the crack is somewhat the same as that calculated for the corresponding downward-breaking cone.

Usually pressure ridges are treated as granular material
according to the principles of soil mechanics. This may hold true with the loose parts of the ridges. With a narrow vertical structure it could further be assumed that the consolidated part inside the ridge fails by crushing. The Kemi I cone showed no clear pattern in ridge penetration. Sometimes thick rafted ice was bent but some ridges seemed to be crushed completely.

5 COMPARISON: FULL SCALE - MODEL TESTS

If the conclusions drawn from model tests are to be reliable, the phenomena in model scale should correspond as closely as possible to those in full scale. In the small-scale model tests in WARC the ice behaved in the same way as in full scale, when the failure was by bending. The broken ice pieces were larger in WARC than in Kemi I in the same scaled conditions and the same failure mode.

Accumulation of ice in front of the structure and on the top of the cone, and collapsing of the cracked ice sheet under the weight of ride-up ice, were observed in WARC just as they occurred in nature. In the test in Oulu the collapsing or accumulation of ice seldom existed, which may be a consequence of the model ice properties. In Oulu the ice behaved like the ice sheet moving at very slow speeds in Kemi I. The greatest discrepancy between the model and full-scale tests was the absence from the model tests of the crushing mode failure of the level ice sheet observed at Kemi I. Attempts were made to trigger the crushing mode by piling ice brash manually in front of the model before the test run, but without success.

In the ridge tests, the ice mass rode up to the same extent as in full scale, but crushing of the ice into small fragments, which took place at Kemi I, was not observed. The difference was caused by the test ridge, which was made by breaking up the ice field and pushing it between two walls. The rubble was then allowed to freeze and consolidate for a while. However, the model rubble
lacked the uniform ice sheet traversing the ridge; natural ridges can even have a stiff rafted ice layer inside.

6 CONCLUSIONS

The ice force records from the Kemi I test cone are so far only preliminary and more attention has therefore been paid to the mechanisms of ice failure. From the observations made at Kemi I and the model tests in WARC and at the University of Oulu, the following conclusions can be drawn:

- The system supporting the Kemi I cone has worked properly. The rubber bags in the gap between the cone and the lighthouse shaft have been sufficiently stiff, allowing the cone to move only fractions of millimetres under ice loads.

- In the model tests with level ice, more satisfactory results were obtained with WARC's fine-grained model ice than in the very small basin with urea-doped ice at the University of Oulu. At very slow speeds the ice failure at Oulu was similar to the failure process in full scale, but at higher speeds the tests in WARC were more realistic.

- The piece size of failing ice in full scale usually accorded with Ralston's /3/ model. In the model tests the distance of the circumferential cracks from the cone waterline corresponded to Ralston's model when cosine-shaped cracks were used and this form was also observed in tests, particularly at Oulu. The full-scale cracks were always roughly circular. The shape of the crack has no significant effect on the magnitude of the ice force.

- The crushing failure mode of level ice observed in full scale never predominated in model scale.
7 REFERENCES


PAPERS PRESENTED AT POST-CONFERENCE SEMINAR
AT ILULISSAT/JAKOBSHAVN
BRIEF PRESENTATION ON PORT AND COASTAL STRUCTURES IN ICE - SOME AMERICAN AND CANADIAN EXPERIENCES

Port structures in ice include mound and other structures for protection of vessels against wave action in ports. Coastal structures shall provide protection against wave action on shores. Mound structures may also be built as protection against sedimentation. Other structures include piers (fixed and floating), and terminal structures for oil, gas and ores.

Port Structures

The experience with rock mound and vertical wall structures in the Arctic is similar to the general experience elsewhere. Ice may climb up on mound structures, but not easily on vertical walls. The experience from Duluth, Minnesota on Lake Superior, mentioned below, is descriptive in this respect.

Example Nome, Alaska

The Nome terminal in Alaska (under construction in 1985 - 86) is a recent example of a new mound structure for the Arctic. Fig. 1 shows the original layout (Sackinger and Bruun, 1983). The structure being built has no shoreparallel section. Vessels will berth at a floating dock on the "left-side".

The following is in citation from Sackinger and Bruun (1983) and Bruun et al (1985):

"THE NOME TERMINAL
NORTON SOUND, ALASKA"

The Nome Terminal shall serve future offshore activities in Norton Sound together with growth in commercial and mining operations. Layout is shown in Fig. 1.
This terminal is composed of a 1200 m causeway, a 270 m head at 9 m depth with a quay on its inside.

The proposed port facility is subject to sea ice for about 7 months every year, as well as the possibility of substantial waves from the SW during the summer months. Consequently, two different kinds of criteria: Ice and Waves, had to be considered.

**Ice Design Criteria**

A review of available satellite imagery of ice in the vicinity of Nome revealed that the slightly concave shoreline geometry extending from Cape Nome (22 km east of Nome) to Sledge Island (38 km west of Nome), as shown in Fig. 1, served to collect drifting ice in many instances during winter. The presence of Sledge Island seems to enhance this trend. Very little ice is in the area during October and November. Consideration of the average number of freezing degree days at Nome and sea ice thickness calculation based upon the relation given in Zubov/35/ suggests that some floes of 30 cm thickness may be found at the end of November. However, the winds in Norton Sound cause substantial ice activity well beyond this date, and it is in December and January that the drifting floes tend to form shorefast ice at Nome. The Nome causeway will probably intercept drifting ice floes in November and December, however, and the possibility exists that shorefast ice such as is usually found in February may begin to be formed earlier in the winter, perhaps even in late November. Ice floes restrained by the causeway would quickly form a sheet of shorefast ice, the seaward boundary of which is likely to coincide with the end of the causeway initially, and with the normal Cape Nome/Sledge Island boundary later, in midwinter. Severe storm conditions with wind from the southeast, the west, or the south could drive loosely-packed ice floes onshore in early winter, before this shorefast ice sheet forms a frozen and consolidated buffer zone for the region around the causeway. The problem of ice floes riding up onto the causeway for the southeast or northwest, and rideup onto the seaward face of the end of the causeway due to ice movements from the south was thus identified and a model study was
initiated, the results of which are reported elsewhere."

For details the reader is referred to Sackinger and Bruun (1983) and Bruun et al (1985) which also describe various breakwater profiles for Nome including the S-profile which has advantages on stability for waves and ice.

Canadian mound structures for ports are usually located in protected waters. An example is the Cape de Meuille breakwater in the St. Laurence Bay on the Magdalena Island. It is a Dolos block structure. Some of its blocks have been damaged, but not necessarily by ice action, rather by wave exposure. Ice will, of course, be able to damage slim elements as they are found in the Dolos block configuration.

Coastal Structures

Regarding mound and wall structures for coastal structures the experience from Duluth, Minnesota on Lake Superior is unique. Here on a relative short section of shore we find examples of the function of ice rubble on the nearshore bottom Fig. 2, ice on a rock mound (Fig. 3), and ice on a mound backed by a vertical wall (Fig. 4), all demonstrating characteristic features of the ice/structure interaction. See Bruun and Johannesson (1971). For relocation of highway 35 a vertical crib wall was prefered, as described by Rottinghous (1971) to minimize the chances of ice climbing over the wall, at the same time to decrease spray and splash by the permeability. Bruun and Johannesson (1971) report on observations of pile-ups on sloping as well as vertical structures.

In cit.:

"Field data from Lake Superior

At Duluth, Lake Superior, northeasterly winds cause westward ice drift. When the ice runs aground on the shore, or is stopped in front of coastal structures, it builds up pressure ridges above the surrounding field usually at some distance from the point of contact. Storms may form more ridges in front of the first ridge. Before Lake Superior
froze over during the 1966/67 winter season, a total of three ice ridges developed west of the Superior Entry. Surveys revealed that ice climbed to 9 m elev. on a rock reef with slope 1:5 to 1:10. The actual thickness of the ice from bottom to crest of ice pile may have been of the order 9 to 12 m. Ice pilings of various heights were observed on all slopes. Vertical walls, however did not cause ice pilings.

Based upon observations in the field the following general conclusions were drawn:

(a) Sloping shores and structures favor ice pilings. As a result of wind and current forces, ice may pile up to elev. of 10 to 15 m above still water level.

A berm or platform incorporated in the structure caused somewhat less ice piling than a corresponding straight rubble mound, mainly due to the "delay" obtained in filling up the platform with ice.

(b) Vertical wall do not favor ice pilings. If the depth in front of the structure is sufficient the ice does not climb, but is rather forced down."

Straumsnes and Bruun (1971) compared spray and splash conditions for some typical permeable coastal structures, and the influence of ice floes deposited on these structures on spray and splash quantities. They report in particular on tests on the above mentioned coastal protective structure at Duluth, Lake Superior designed to produce as little spray and splash as possible because US 35 is just behind it, and ice on the highway is undesirable for reason of safety. In cit.:

"TEST PROCEDURES"

The following designs were investigated by laboratory experiments carried out partly at the St. Anthony Falls Laboratory, Minneapolis and partly at the Technical University of Norway. Model scale was 1:30. All figures refer to prototype values.
A) Straight rubble mound with a slope of 1 in 2, and block weight = 8 t.

B) Rubble mound with a berm. Lower slope 1 in 2 up to elevation 0.9 m above water level, slope of berm 1 in 5 up to elevation 2.7 m, then an upper slope 1 in 3 to elevation 6.0 m above water level. The total width of the design was ab. 33 m. Block weight was 8 t.

C) Vertical permeable crib design, consisting of a pile frame surrounded by netting and filled with blocks. Block weight was 3.8 t.

Common for the three designs was crest elevation = 6 m, depth at the toe of the structure = 6 m, and slope 1 in 5 from the toe of the structure at elevation 6 m below water level down to the bottom at elevation 9 m below water level.

The straight rubble mound

The results from tests on the straight rubble mound showed that this design was very sensitive to variations of h/H. h = wall elev., H = wave height. The relative spray quantity \( Q/HL \) (L = wave length) increased with decreasing h/H. Waves with steepness ratio \( k = H/L \approx 0.08 \) gave more spray than waves with \( k \approx 0.04 \), when the relative crest elevation h/H > ca. 1.2, and vice versa, when h/H < ca. 1.2.

Tests with ice floes on the water surface showed too much scatter to justify any conclusions. The tendency, however, was that ice floes increased the relative spray quantity by 50-100%. In this connection it must be noted that the ice floes (ab. 100 wax floes) had a slight damping effect on the waves as most of them were concentrated in the breaking zone. Some of them were deposited on the slope.

The berm wall

The results from tests on a berm wall showed that \( Q/HL \) was nearly independant of variations in h/H within the range h/H = ca. 1.0-2.0. Waves with steepness \( k = 0.08 \) caused more spray than waves with \( k = 0.04 \) when the ratio h/H > ca. 1.2, and vice versa for h/H < ca. 1.2.
Tests with ice floes on the water surface showed almost the same scatter as the corresponding tests with the straight rubble mound. Also in this case ice increased the relative spray quantity by 50-100%.

The crib

Results from tests on the crib showed that results were very sensitive to variations in \( h/H \). The relative spray quantity \( Q/HL \) increased with decreasing \( h/H \).

Ice floes on the water surface decreased the relative spray quantity by more than 50%, a result of the damping effect by the ice, which had no possibilities for depositing on the structure.

Special Arctic Feature on Coastal Erosion

Coastal erosion in the Arctic is influenced by the climate conditions. The formation of thermoerosional niches into frozen bluffs due to storm surges on the Beaufort sea coast is described by Kobayashi (1985).

In cit.:
"An analysis is made of the formation of a thermoerosional niche into a frozen bluff due to a storm surge on the Beaufort Sea coast. As a first attempt, the problem is treated as a one-dimensional unsteady problem in which the vertical melting front of the thermoerosional niche migrates into the frozen bluff under the thermoerosional action of breaking waves inside the surf zone during a storm. The analysis examines the temporal and shore-normal variations of the temperature and salinity of the seawater and the concentration of suspended sediment resulting from the migration of the melting front into the frozen bluff. A simple analytical solution is obtained for the case where the mean water depth during a storm is approximately constant in the neighborhood of the frozen bluff. An example computation based on the simple analytical solution indicates that the thermal driving of the ambient seawater, the mechanical driving represented by the water depth, and the duration of the storm surge are important in determining the degree of the thermoerosional niche formation in the frozen bluff. The computed results are also shown to be in qualitative agreement with available field observations."

Offshore Structures in Ice

They have become numerous in American and Canadian offshore waters, and range from the monopod in Cook Inlet to the many caissons, often cone-shaped fills and fills combined with caissons, built in the Arctic of the US and Canada, as well as in St. Laurence Seaway. The POAC-INDEX (1985) gives numerous examples of such structures and on the ice-structure interaction to which the reader is referred.

The most recent development has been in the large fill islands in the Alaskan and Canadian Arctic Sea. The largest island built so far in the Arctic is the Issungnak Island described in the May 1983 issue of DREDGING AND PORT CONSTRUCTION. It is a steel caisson retained island designed to withstand ice and wave action in the Beaufort Sea. Another, and construction-wise more interesting island is the TARSIUT ISLAND (Fig. 5).

The island exists of an underwater sand berm with side-slopes of 1:5 from -22 m to -7 m. On top a stabilizing 1 m thick layer of gravel is placed. Four concrete caissons (80 x 15 x 11 m) penetrate the water-level and are placed in a square. The caissons and the area in between are filled with sand, reaching a final level of of +7.5 m.

Sand was used to build up the underwater berm. As no sand was available at the island site an investigation for borrow areas was started. Prior to the placing of sand a 4 - 5 m thick soft silty clay layer had to be removed. This was done by the trailer dredger "Geopotes X." Due to the draught of this vessel (- 11m) sand had to be transported over a distance of more than 100 km. At a distance of only 20 km there is a large sand/gravel bank at a level of -7 m.

In order to be able to realize the island construction in one summer season "Canmar" decided to equip the "Aquarius" with a barge loading system. The dredger continued to work as a cutter-suction dredger as the sand/gravel layer was only 1 - 2 m thick. Thanks to the seaworthiness of the dredger she was able to continue working in up to 1.5 m wave height. At this point the movement of the empty barges alongside the dredger was so heavy that work had to be interrupted.
At the location in unprotected waters at a distance of 50 km from the shore the workability was approximately 70%.

The barges used were Manitowoc splitbarges type 2000 (1500 m³). These non-selfpropelled barges were towed from the borrow area to the island site by tugboats, and due to the split-type dumping of the material could be executed very quickly commanded from the tugboats by radio. The barges were loaded with 1400 m³ material in approximately 45 minutes, and the turnaround time was approximately five hours. Since only five barges were available it is clear that the dredger had to lay idle from time to time to wait for barges.

In order to economize on sand used, a study was made of the possibilities to build an island with steeper side slopes.

In the Netherlands several projects have been realized with steep side slopes using a special placing method. The sand-water mixture is pumped through a discharge pipe hanging vertically from a barge till just above the bottom. The pipe widens at the end in order to reduce the velocity of the mixture. The sand will now settle gently on the bottom, or on the already realized part of the berm, and steep slope will result (see Figs. 5).

In exposed areas a classical method is to dump sand with dump barges or trailer dredgers. The dumped sand falls down as a compact mass creating a vast hole at the point of impact and slashing sideways. After several loads a slope with a ratio of 1:10 to 1:20 will develop.

As this was not acceptable, "Dom" developed the idea of using the discharge pipe method, and for the first time even using it in exposed waters. This meant that all floating equipment used must be seaworthy, and therefore had to be specially developed or adapted.

The "Hendrik Zanen" and the "Geopotes X" were equipped with a quick coupling system which connected a flexible floating pipeline to the dredger while the pipeline was connected to the discharge barge at the other end.

At the end of the floating pipeline a male balljoint was connected.
This heavy steel part was kept afloat by a Yokohama floater. Once the trailer dredger arrived at the site a fishline was handed over by a tugboat. The fishline was connected to a heavy winch at the bow of the trailer dredge. This winch was placed just above a female ball joint at the end of the discharge pipeline aboard the trailer dredge.

By heaving the steel wire the male ball joint came into a guiding system, and was then pulled into the female ball joint by means of a hydraulically operated hinge system.

The discharge barge was an offshore crane barge with living quarters to which the discharge pipe had been assembled.

The barge was further equipped with a sophisticated radio localisation system and a computer controlled position printing system. This system was SYLEDIS, a very accurate system with a long range.

The system was very reliable, and during the project no delays occurred due to breakdown of the system. All soundings were carried out by a tugboat with automatic sounding equipment. The recordings were taped, and then plotted aboard the discharge barge. During the execution of the project continuous soundings were carried out to register the development of the underwater berm. The dump barges which were used in addition dumped their loads in the center of the island. Once the level of -7 m was reached a gravel layer was placed.

The trailer dredgers dumped their load of gravel to the discharge barge where a special designed divider system was used to spread the gravel evenly on the bottom. During this pumping operation the discharge barge was moved over the area. All movements were carefully recorded to create an even layer of gravel.

As tolerances were as limited as \pm 0.1 m a heavy steel beam was suspended from the barge to the final level of -6 m, and the top level was "screeled" by pulling the barge with the beam over the area, finally the caissons were placed. The caissons were floated into the area and positioned using the barge as a guiding system while fixed on anchors. The trailer dredger was used to ballast the cais-
sons with water which did sink the caissons to the bottom. After having checked the final position of the caissons these were then pumped full of sand by the trailer dredger.

When all four caissons were placed in a square the corners were sealed off by a heavy steel door and sand retaining fabrics. Thereafter the area in between the caissons was filled with sand pumped by the trailer dredger till the final level was +7.5 m. During a very heavy storm one of the doors was knocked out, and most of the sand flowed out of the inner area. With the aid of sheet piles and a special very heavy sand-retaining mattress the leak was sealed, and the area filled once again. No further leakages occurred thereafter.

During the second summer season (1982) the top of the caissons was raised by placing stone gabions, as during stormy periods a lot of waterspray hampered the drilling operations. At this point in time the Tarsiut island has safely survived one summer season and two winter seasons."

Later experiences have been satisfactory too.

Terminal Structure in the Arctic, Example
LNG Terminal for Arctic Conditions

Development of gas resources in the Arctic is progressing rapidly, but it calls for special installations and designs. McDonald (1980) describes the design of an LNG terminal in the Canada Arctic (Fig.6). The site is the Melville Island, typical of most of the high Arctic islands, underlain by sedimentary rock such as sandstones, siltstone and shales. Generally, the offshore bottom conditions around these islands are characterized by gradual slopes with very soft silty clays overlying permafrost, with the exception of creeks and river deltas where, near the shore, the sea bottom is covered with fine sands which are part of the submerged delta. Therefore, the sea bottom conditions generally consist of either soft clays or loose sands, and are not ideal for the construction of wharfs or causeways. It was necessary to select a harbor based on suitable bathymetry and ice protection considerations, and design for the generally poor soils.

At the terminal site the nearly horizontal delta area is in a perma-
frost condition to a 2 m water depth. At an offshore water depth of 16 m the seabottom is underlain by about 15 m of silty sands followed by firm silty clay, and the permafrost is generally more than 30 m below the sea bottom.

The seabottom conditions required a further review of the terminal layout. In a geotechnical evaluation it was found that the sea bottom could not support the embankments required for the wharf and the barge enclosures with any degree of safety because of the excess pore pressures which would develop during construction. The stability problem was further compounded by the additional weight of the wharf cells within the embankment. A summary of different Factors of Safety as a function of construction pore pressures is shown in Table 1.

<table>
<thead>
<tr>
<th>Slope</th>
<th>Porewater Pressure</th>
<th>Minimum Factor of Safety</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5:1</td>
<td>0</td>
<td>1.28</td>
</tr>
<tr>
<td>1.5:1</td>
<td>30</td>
<td>0.88</td>
</tr>
<tr>
<td>1.5:1</td>
<td>60</td>
<td>0.52</td>
</tr>
<tr>
<td>2:1</td>
<td>0</td>
<td>1.58</td>
</tr>
<tr>
<td>2:1</td>
<td>35</td>
<td>1.12</td>
</tr>
<tr>
<td>2:1</td>
<td>70</td>
<td>0.69</td>
</tr>
<tr>
<td>3:1</td>
<td>0</td>
<td>2.10</td>
</tr>
<tr>
<td>3:1</td>
<td>30</td>
<td>1.63</td>
</tr>
<tr>
<td>3:1</td>
<td>60</td>
<td>1.05</td>
</tr>
</tbody>
</table>

The causeway is at a shallow water depth and founded on permafrost. The barges have been placed inland in basins excavated from the permafrost material. This proposed layout is shown in Fig. 6.

Design analysis showed that the significant loading on these cells would be due to ice forces. The inlet in the winter is covered with ice of approximately 2 m thickness, but without significant ridging. A long term impulse is required to mobilize the cell and surrounding soil mass, and during such a thrust the average force will be 46,000 kN (4690t) on a cell, and has been used to calculate
its overall stability. Higher stresses which could cause rupture by internal shear can be developed in a relatively short time. Such internal shear is generated by the maximum force which occurs just before a flack of ice is pushed out of a sheet. This peak force is 80,800 kN (8237t). A concentrated force of 38,400 kN (3915t) has been estimated to happen anywhere within the ice belt and local stresses have been calculated using this force. A summary of various failure mechanisms which were analyzed is shown in Table 2.

During the preliminary design phase it was concluded that earthquake ground motions would not affect the cell stability. The most critical period would occur during construction when pore pressures would be highest. Melville Island was classified as a Seismic Zone 2.

Table 2 Factors of Safety for Various Failure Mechanisms

<table>
<thead>
<tr>
<th>Failure Mechanism</th>
<th>Actual</th>
<th>Recommended</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Excessive interlock tension</td>
<td>2.3</td>
<td>1.5-2.0</td>
</tr>
<tr>
<td>2 Excessive vertical shear on centreline of cell</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(a) Due to impact load</td>
<td>1.4-3.0</td>
<td>1.25-1.5</td>
</tr>
<tr>
<td>(b) Due to long term load</td>
<td>1.5-3.5</td>
<td>1.25-1.5</td>
</tr>
<tr>
<td>3 Tilting (horizontal shearing)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(a) Due to impact load</td>
<td>1.2</td>
<td>1.25-1.5</td>
</tr>
<tr>
<td>(b) Due to long term load</td>
<td>1.4</td>
<td>1.25-1.5</td>
</tr>
<tr>
<td>4 Stability of sea bottom slope and single cell</td>
<td>1.6</td>
<td>1.5</td>
</tr>
<tr>
<td>5 Overturning</td>
<td>2.9</td>
<td>3.0</td>
</tr>
<tr>
<td>6 Base stability</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(a) Bearing capacity</td>
<td>4.2</td>
<td>3.0</td>
</tr>
<tr>
<td>(b) Pile friction</td>
<td>14.0</td>
<td>3.0</td>
</tr>
</tbody>
</table>

with peak ground accelerations between 3% g and 6% g. After submission of the Project Plan for approval by various Federal regulatory agencies however, APP was notified that seismic information accumulated in very recent years shows numerous significant earth-
quake occurrences in this area. The design, therefore, has been re-analyzed to take into account peak ground accelerations of 14\% g to 18\% g.

In addition to the accelerative forces on the cells themselves the wharf structure has been re-analyzed to include forces affecting the overall dynamic stability of the sea bottom containing the cell and also the loss of strength from the liquifaction potential of the upper, loose, silty sand.

To produce a design to meet the above considerations three methods were reviewed:

- Chemical grouting of the sea bottom
- Vibro-compaction/replacement of the loose sands with rock fill
- Foundation of the cells at a greater depth

The chemical grouting method was not considered seriously because of the low permeability of the silty sand.

The vibro-compaction/replacement process was considered because of its improvement of the sea bottom due to a combination of some compaction, reinforcement of the soils by rock columns (replacement), and finally, improvement of conditions by the drainage paths the rock columns would provide. However, partial disadvantages of this design are that it would have to be preceded by a field test program, and a longer period would be required for completion of the wharf.

The most positive design would be to found the cells at a greater depth, on the underlying hard stratum or permafrost known to exist some 30 m below sea bottom. Discussions are continuing with various contractors to determine whether or not the piling will have to be a more rigid HZ section to permit driving to these depths."

The above was just a few examples of ice actions, anticipated or actual on structures in the American and Canadian Arctic. There are many other good examples. The reader should consult the POAC-INDEX by E. and P. Bruun (1985).
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(3) Bruun E. and P., 1985, INDEX, POAC 71 - 85, printed by the Danish Hydraulic Institute, POAC-85, Greenland.


(5) McDonald, A.F., 1980, "Design of an LNG-terminal in Canada's High Arctic", Ports-80, printed by the ASCE.

(6) Rottinghaus, B.H., 1971, "Shore Protection Study for a section of US Interstate 35 in Duluth, Minn. POAC-71, Norwegian Institute of Technology, Trondheim.


Fig. 1 The NOME Terminal in ALASKA. Dotted lines indicate the terminal which is being built (1985-1986). See ref. 7.
Fig. 2 Ice-piling at DULUTH
LAKE SUPERIOR

Fig. 3 Ice-piling on Rock Mound
LAKE SUPERIOR

Fig. 4 Ice-piling at vertical wall
LAKE SUPERIOR
Fig. 5 Cross-section of Tarsiut Island with discharge barge (not to scale). Dredging and Port Construction, 1983.
Fig. 6 The BRIDPORT terminal, MELVILLE ISLAND, N.W.T., Canada (MacDonald, 1980).
12 YEARS PROGRAMME FOR BASELINE STUDIES IN JAMESON LAND

3.1 Identification of Vulnerable Areas is a study finishing several years' attempt to by the way of aerial photos to determine the ability of the active layer to stand up to influences from driving and research activities. The study includes the localization and verification of areas in Jameson Land where the active layer in periods cannot stand up to the activities mentioned.

3.2 Geotechnical Description in Outline of Affected Areas is an elucidating geotechnical study of the areas where drilling and exploitation, transport and storage of hydrocarbons can be expected. Due to reasons of time the study will mainly include areas where detailed seismic work is to be undertaken.

3.3 Topgrafical Mapping in Outline of Affected Areas includes the making of outline maps where boundaries and conditions of great importance for the protection of surroundings, man, and material need to be determined and described. E.g. vulnerable vegetation and soil, non-bearing soil and areas with a risk of avalanches.

3.4 Determination of Climate Variations and Derivative Changes of the Active Layer The study includes the collection and processing of climate data and soil temperatures. A current registration at a centrally situated climate station in Jameson Land is undertaken. In addition instantaneous values are received via satellite from the climate station and from a network of small temperature measuring stations scattered over that part of the country.

The data mentioned will partly be used for an evaluation of the concessionaires' proposals for material and plants, partly for the determination of frost lines and accumulated amounts of cold in the active layer and the snow's thickness. With this knowledge it can be determined if the active layer can stand up to the impact of driving and work and a decision on start and discontinuation of activity in the area can be made.
3.5 The Distribution, Danger, and Use of Snow as a Base for Driving

The snow studies includes a mapping of distribution patterns, melting phenomena, avalanche danger, and the study of the snow's ability to delay the freezing and the thawing of the active layer.

The snow study will also show, which thickness, density, and hardness the snow must have to be able to protect the active layer and possible vegetation from the impact of driving with heavy vehicles and activities connected to this.

4.1 Navigation in Connection with Exploration, Field Construction, and Exploitation

The study includes hydrographic measurements from ship, remote sensing from satellite and aeroplane supplemented with "ground true" measurements in the ice of the fiords at Jameson Land and in the pack ice belt offshore, as well as construction and running of an automatic recording, satellite-monitored climate station in the area of Aarhus Bugt.

The information collected will be used to compare the consequences of different proposals for placing terminals in Jameson Land. The question is of partly a shipping terminal for hydrocarbons, partly a harbour that can receive constructions, material, and material for construction of fields for the extraction of hydrocarbons. The information will also be used for specific details of the basic demands on ships, navigation, and contingency plans.

4.2 Combatting Oil Spill in Connection with Navigation

The study is based on the knowledge acquired during project 4.1 and the marine biological studies of GFM (= Greenland Fisheries and Environmental Investigations) and includes an evaluation of experience and an attempt to track, survey, collect, or in other way combat oil spill in arctic waters.

The results are to be used for specification of demands on and evaluation of the contingency plan for oil spill, which will be sent in for approval.
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DEVELOPMENT FOR THE FUTURE YEARS - GREENLAND

During this POAC 85 conference in Greenland and especially the seminar here in Ilulissat we have been listening to a number of distinguished speakers outlining firstly the state of the art on a variety of scientific topics and secondly the present situation as regards the application of various disciplines when describing and trying to solve important problems faced in today's Greenland.

I shall only mention a few:
- baseline studies for oil exploitation
- plans for hydro power schemes
- energy planning and
- actual exposure to heavy metals in Greenland.

Incidently is now my task as an official in the Greenland Home Rule administration to sort of close this seminar whereas the original scheme called for one of Greenland executive members or ministers to open the very same seminar.

Please bear this in mind if - during the next minutes - you should get the impression that my speech maybe is a bit too politically biased to be delivered by a civil servant who once was a civil engineer.

In his speech at the opening of the POAC 85 conference down in Narssarssuaq, Premier Jonathan Motzfeldt mentioned that the Home Rule over the coming years shall be taking over from the Danish state some very large areas of responsibility - that is: technical matter in a broad sense, through the transfer of Greenland Technical Organization (GTO), and the transportation and supply of goods within Greenland, through the transfer of the remaining part of the Royal Greenland Trade Department (KGH).
Both of these two steps is the result of a new Greenlandic attitude towards the process of transferring responsibility because it is planned to take place in a fairly speedy manner without trying to divide the areas and/or organizations into smaller parts before transfer.

Only the coming years can show whether or not the expected advantages of doing so will come true. However, it is true that the preparation for and negotiations about the economic terms in taking over the part of the Royal Greenland Trade Department being responsible for the operation of its trawler fleet, its fishing industries and the marketing of fish products have been so lengthy and hard that it was necessary to look for another strategy.

Prior to and especially upon the transfer of GTO which is to take place on January 1st, 1987, the Home Rule authorities will have to enter into negotiations with the Association of the Greenland Municipalities, KANUKOKA, with the aim to delineate the roles of the Home Rule and the municipalities respectively when possibly splitting GTO into minor parts after its transfer in one piece.

This work is expected to follow what is outlined in a report prepared by the working group chaired by the Danish High Commission to Greenland and issued some 15 months ago when it was still expected that the transfer of GTO would be gradual and with certain elements of GTO being transferred directly to the local municipality level.

To put it shortly you can say that the Home Rule wants to take over the role of the Danish State before dividing and decentralizing GTO.

For the 5 year period between 1985 and 1989 the Greenland Home Rule has launched a development plan regarding the sector of renewable resources.
This 5-year period coincides with the 5-year agreement reached with the EEC in connection with Greenland leaving the European Communities on January - or actually February - 1st this year.

Until 1989 the EEC member countries are allowed to catch a yearly specified quota of fish which the Greenland fishing fleet of today does not have the capacity to fish.

In return the Home Rule receives a grant of 216 mill. DKK per year and it is primarily this sum that forms the economic basis of the development plan.

The plan has several goals:

1) to ensure that Greenland herself becomes able to fish and exploit an increased amount of the total resource base, or the total allowable catch, the TAC.

2) The modernization of the fish processing plants in the towns and the restoration of the worn-out facilities in some of the approximately 60 hamlets throughout Greenland.

3) To double the fishing capacity through the development of the local coastal and inshore fishery and through directing the offshore fishery towards already known but yet not exploited species, such as redfish, Greenland halibut, flounder, Canadian greenadier, blue whiting, wolffish, capelin, and scallops.

4) To ensure the hunters' occupation through increasing the sale of sealskins, especially sealskin products, and through supplemental production of fish and meat in the hunting districts.

5) To ensure increased employment opportunities within the fishery and processing sector.

As probably everyone can imagine this calls for substantial financial support. To be more specific it is the intention to spend some 130 mio. DKK per year.
In order to give you a very fresh example of the kind and size of the future investments I may inform you that the Home Rule government only yesterday consented to an agreement with the Ministry for Greenland regarding the improvement of the fish processing facilities and related infrastructure in Aasiaat/Egedesminde, some 80 km from here at the 'corner' of the Disko Bay.

According to this agreement the Home Rule will invest some 57 mio. DKK in 1986 and 1987 in a new fish factory whereas the ministry will invest 45 mio. DKK in the same years, mainly in new quay structures at the site which is separated from the existing harbour facilities.

Furthermore the Home Rule will assist the Ministry with an extra 15 mio. kr. to ensure the necessary infrastructure, despite the fact that this is still a state task.

I believe it is fair to say that such investments in a completely new and separate harbour will be untypical as the future needs for extra harbour facilities can be met through expansion of existing ports etc.

To conclude it should be stated that maybe the need for changes and reinvestments in this fishery sector can be illustrated by the fact that 1984-result of the sector was a deficit of 150 mio. DKK which corresponds to one-fifth of the gross turnover, from fishing over processing to marketing.

However, a percentual deficit of this size is not unusual when you compare Greenland with northern Norway, the Faroe Islands, or Iceland. What differs is the internal relationship between the results of fishing, processing and marketing of products.

Here in Greenland the prices paid to the fishermen generally do not correspond to the actual value of the landed fish because there is a subsidy to cover some of the bunker oil costs on the basis of the amount of landed fish. That is: If the processing
or the production should break even the fishermen would go bankrupt fairly quickly with catastrophic consequences for the investments in the private fishing fleet catching any fish, besides shrimps and salmons.

Consequently, you can see a growing tendency in the Home Rule fish processing entity towards taking over originally privately owned plants. But of course everyone in the Landsting, and possibly also in the Ministry, are anxious to learn whether or not the above mentioned efforts will pay off.

Following this brief discussion on the renewable resources I should like to turn to the area of non-renewable resources.

First of all I will present an overhead slide showing the geographical distribution of the actual licences and concessions as of June 30, 1985.

As you can see there is a rather limited number of companies investigating or exploring for a variety of minerals which may or may not be found in commercial deposits.

At present there is only one mine operating in Greenland, 'The Black Angel' in Maarmorilik, some 200 km north of here, where approximately 675,000 tonnes of ore are mined annually. The resulting production consists of 125,000 tonnes of zinc concentrate and 25,000 tonnes of lead concentrate which also contains small amounts of silver.

The export value, FOB Maarmorilik, of the shipped concentrates, has varied considerably through the years. In 1983 it amounted to 441 mio. DKK to be compared to a total Greenlandic export of 1,645 mio. DKK that year.

At present steeply decreasing world market prices of zinc have forced the company to cut the labour force by some 45 out of 350 employees.
In 1985 there is a risk of Greenex A/S coming out with its first negative result. In 1984 the company had a surplus of 73 mio. DKK – before payment of public fees, and in 1983 this number was 120 mio. DKK.

Since 1973 Greenex has had a total result of approx. 900 mio. DKK, out of which the shareholders have received a dividend of 600 mio. DKK and the public revenue is 250 mio. DKK. It may be added that the Greenland individual income tax revenue amounts to an extra 100 mio. DKK sofar.

Today it is rather uncertain to evaluate the remaining lifetime of the Greenex mine because it is primarily dependent on whether or not it is feasible to mine the ore and not – as has been the case generally – the ore reserve itself.

However, despite some rather disappointing exploration results in the area during recent years the remaining ore reserves amount to some 5 years of continued operations at present rate.

At present there is no other mining companies having actual plans of entering into exploitation of hard minerals in Greenland. Furthermore, the necessary leadtime before production start may very well be of the order of 10 years from now.

The very same thing can be stated about the lead times of starting oil production in Greenland. As shown on the slide there is only one concession in force that is the concession given to a consortium led by Arco Greenland in Jameson Land, a 10,000 square km land area in East Greenland.

Furthermore it must be stated that the area is a high-risk area with rather substantial probabilities that the concessionaire surrender his rights at first occasion given,
that is by the end of 1990 upon obtaining too negative results to justify further exploration efforts.

It is such perspectives that made Premier Motzfeldt state on Sunday, Sept. 8 in Narsarsuaq that the Danish and Greenland authorities over the coming months will start considering the initiation of oil exploration in other areas which may have an oil potential - yet of unknown size.

We shall be doing this with the aim to obtain a steady level of activities and a continuity in operations where there will be different groups of oil companies operating in different areas on different stages of activities, that is seismic investigations, exploratory drilling and hopefully also production.

This should be in the interests of all involved parties:

- the oil companies,
- the governmental regulatory bodies,
- the contractors and manufacturers of equipment, and
- the scientific world

because there will be an ever existing need for research and development of new technology that meets the requirements of the harsh climate and properly protects the fragile arctic environment.

In modern concessions in the North Sea it is now customary to demand every concessionaire to enter into a formal agreement on funding research and development projects for the benefit of domestic spin off to private firms, research institutions, and universities.

Unfortunately we were not able to reach agreement with ARCO during the concession negotiations that such a formal agreement, including a specified amount of money, should be entered into after granting the concession itself.
Consequently, in the concession we are faced with a provision that is less binding for the concessionaire as regards the obligation to involve national research institutions, development organizations and the industry in scientific investigations, research and technological development that one could prefer.

As you can imagine this fact is one of the driving forces when considering the possibilities and benefits of opening new areas for hydrocarbon exploration and the mistake shall not be repeated.

Without forgetting what I just said about the present economic outlook for Greenex' operations in Maarmorilik and the rather long lead times before a possible new exploitation of 'hard' minerals and/or hydrocarbon may be initiated I shall now touch upon the question of sharing of the public revenue between Denmark and Greenland.

As things are now it is an integral part of the whole Home Rule scheme that any public revenue in the form of royalties, company taxes, dividend taxes, profit shares and income through public or governmental participation as a shareholder or concessionaire shall be transferred to the Greenland Exchequer and subsequently deducted on an annual basis from the expenditures in Greenland of primarily the Ministry for Greenland.

If the total amount of such mineral revenues exceed the annual expenditures of the Ministry either party is entitled to call for negotiations on how to split such a surplus.

In general the situation will be that Denmark is reimbursed while Greenland gradually becomes more financially selfsufficient - hopefully at least.

However, this arrangement contains no real incentive for Greenland to consent to any new resource exploitations because such operations will not really increase the total income to the Greenland Exchequer - it will as a matter of fact only alter the composition of the income volume.
This is the reason why the Greenland Home Rule intends to enter into negotiations with the Danish Government with the aim to re-formulate this revenue sharing principle in such a way that Greenland receives a fair share of the revenues without an equal reduction of the Danish expenditures.

Naturally, one can foresee rather difficult negotiations about the size of that share and it is probably quite unrealistic to put it much higher than 50 per cent, but that may also be considered as a positive outcome.

Especially if Denmark and Greenland could consent to an arrangement where - at least some of the remaining revenue - is allocated to a fund which may assist in financing - for example - the prolongation of the rather costly investigations leading to the future exploitation of hydro power in Greenland.

Please bear in mind that the above mentioned considerations primarily deal with the situation today when there is only one mine in operation.

If oil production actually starts at some point in time it is my impression that the revenues then in question will be of quite another order of magnitude - billions of dollars instead of millions of kroner.

Consequently, we will be faced with problems of quite another order of magnitude and nature, i.e.: how to screen the existing fragile economy from at least some of the negative impacts when becoming dependent of revenue from oil production. I shall only mention the effect of uncertainties with regard to oil prices and currencies plus the operation cost when producing oil in an arctic area.

This calls probably for the establishment of a so-called 'buffer-fund' which should have the purpose of protecting our economy from fluctuations in the oil revenues.
For comparative reasons I may inform you that the Norwegian Storting recently have agreed almost unanimously to the principles of establishing such a fund. By the way: In Norway the oil revenues in 1984 were equal to 20 per cent of the gross income to the Norwegian Exchequer.

Before ending I should like to say a few things about the necessary staffing to manage the development in Greenland over the coming years.

As one can imagine there are conflicting tendencies which may take some time to solve. For example: Facing high rates of unemployment is a pronounced Greenlandic political wish that as many Greenland employees as possible actually are employed instead of persons coming from outside, especially Denmark.

Furthermore, there is a wish that as many of the central decision-taking entities are moved from Denmark to Greenland as quickly as possible.

Besides that it is a fact that the average age in the Danish part of the administration is rather high and that the number of Greenlanders with an academic degree still is rather low due to the limited basis for recruiting students.

Obviously, this has to lead to an overconsumption of administrative labour force in the transition period and an inevitable change of generations in the administration as a whole.

Hopefully, this can take place in an orderly manner over a limited time in order to avoid an equal overconsumption of public wage expenditures, which I believe nobody can really be interested in when the productability of the Greenland is at stake.

There is no doubt that there will be a need for non-Greenlandic labour force up here. However, we may see that such labour
force will be described as called-upon employees of the Home Rule and not as labour force sent out by the Ministry for Greenland. Hopefully, this will have an effect that goes beyond the mere psychological one.
NORMAL AND EXTREME ICE AND NAVIGATION CONDITIONS IN DAVIS STRAIT AND DISKO BAY.

For centuries the southern part of the sea west of Greenland has been called the "Davis Strait" or merely "The Strait". New terminology sets the southern border of the Davis Strait at 64° N and the northern border at the Disko Bay. This paper concentrates mainly on the ice and navigation conditions in the area thus defined and on the ice and navigation conditions in the Disko Bay.

Knowledge of the normal ice conditions of a certain area is a great asset when planning any major task in an arctic coastal zone. How long is the navigation season? When does it start? When does it end?

For the Davis Strait and the Disko Bay there are several sources of such information. Data from the area has been collected for more than 100 years. This information - presented e.g. in the year books of the Danish Meteorological Institute - has in Denmark been analyzed for the use in statistics and average limits; but only to a limited extent.

An ice atlas /1/ is based on information collected from 1919 to 1934. The results stand up quite well in spite of the low number of observation years and the relatively few observations.

In 1958 the U.S. Navy Hydrographic Office in Washington, /2/, published an ice atlas with average limits and maximum and minimum extension of the ice. The atlas presents data up to the year 1957.

A more recent Canadian ice atlas unfortunately does not cover the Greenland coastal areas sufficiently.
In 1976 an approach to a considerable statistical work /3/ on the extent of the "Vest-isen" was made in Denmark in connection with oil prospecting off the western coast of Greenland during the years 1975 to 1977. Danish, American and not least Canadian results of flight reconnaissance were applied with a supplement of satellite information.

The publication contains information from the years 1959 to 1974. The data processed by EDP has been published as histograms (Fig. 1). It is relatively easy to supplement as new ice year-books appear.

Fig. 1. West Ice Histogram, 67°30' N for the period July 15. - 21. Information from 14 of 16 investigated years. E.g. in the years 1964, 1966 and 1973 the West Ice covered the sea from Baffin Island to 58°00' W. In 1971 there was no West Ice at 67°30' N. The year-box has been placed on land - to the left of the histogram.

The sea ice normals shown in Fig. 2 are based on similar charts from The Meteorological Office, Bracknell, U.K. They present a good picture of the "normal" ice years at the west coast of Greenland - and that only. One could believe that the maximum extension was covered by 100 years of ice information; but in the period 1982 to 1984 we saw the worst ice winters in the Davis Strait in a century.
Fig. 2. Upper row shows the average extent of the drift ice at the end of each particular month. The charts are based on similar charts from The Meteorological Office, Bracknell, U.K.. Two lower rows show actual ice conditions (Aug 82 - Mar 84). Areas of fast ice indicated in black. The charts are based on charts earlier compiled by Naval Polar Oceanography Center, Washington, D.C., U.S.A. and from Ice Central Narssarssuaq, Greenland.
The mean summer temperature in Godthåb (Fig. 3) was very low as compared to the normal; but the cold weather over Baffin Bay and Davis Strait is a local phenomenon, as it e.g. appears from fig. 4. The phenomenon experienced was on a comparatively local scale and of greater intensity than anywhere else in the northern hemisphere. It was probably related to an abnormally strong deepening of the Canadian upper air cold pool, which at the same time was displaced towards the south-east, the area between Baffin Land and West Greenland.

![Temperature Chart](image)

**Fig. 3.**
- = normals
- = actual mthly.
1) = coldest January on record (1882)
2) = coldest February on record (1898) mean temps.
Fig. 2 shows the development of "Vestis" during the 2 years 1982 to 1984. The low 1982 summer temperatures and the considerable advection of old ice (Storis) to West Greenland during that year, will explain that as late as in August there were still remains of "Vestis" mixed with old ice in parts of Baffin Bay and the Davis Strait. Consequently the low water temperatures, the remaining ice and low winter temperatures, the remaining ice and the low winter temperatures strongly contributed to "The worst ice winter of the century" in 1982/1983.

The 1983 summer temperatures again were low and advection of old ice once more above normal, so by August 1983 even more ice remained in Baffin Bay and Davis Strait as compared to the year before. Due to low temperatures during the winter 1983/1984 the
extension of the "Vestis" equalled the previous record of 1982/1983. Conditions were so unusual that considerable formation of new ice took place all along the West Coast and right into Julianehåb Bay.

Ice charts as shown in Fig. 2 are based on reports from coast stations, aircraft as well as on satellite photographs. A wealth of information; but not all easily utilized. Some ice limits shown are approximated and thus marked with dotted lines.

Conclusion:
With the surprises coming through the years it seems obvious, that a new analysis of all information has to be done in order to produce a better ice atlas and improved ice statistics to be used by planning authorities and companies. This work will demand time and money; but will be an investment giving an impressive economical and scientific return.

REFERENCES:
/1/ Atlas der Eisverhältnisse des Nordatlantischen Ozeans. Deutsches Hydrographisches Institut, Hamburg 1050.
ACTUAL EXPOSURE TO HEAVY METALS IN GREENLAND
NATURAL AND MAN-MADE SOURCES

Pollution surveys concerning the load of environmental toxicants serve partly to secure public health and partly to create basic knowledge for local actions in specific environmental cases. It must be realised that public health problems caused by the rapidly growing industrialization and changes of life style in the arctics cannot be solved by the use of conventional precautions developed under other conditions than those characteristic to the arctics. Environmental control in these areas must be planned now, and will require legal action accommodated to the local situation. This means that a scientific expertise must be developed to cope with the arctic environmental problems which already exist and in the future will be more pronounced.

The major difficulty in evaluating the impact of environmental hazards on humans lies in the fact that effects are often not recognized and will perhaps show up only several decades after the onset of undue exposure.

A relationship between health and quality of environment is now generally accepted. Due to its complexity the question is, however, to some degree controversial. The many aspects of the problem can be summarized as follows:

1) Change of environment: Increasing industrialization and urbanisation; increasing use of chemicals.

2) Change of population: Increasing population size; relative increase in extreme age groups, increasing number and
duration of life of individuals of low resistance, increased mobility in society.

3) Change of problem: Supposed connection between health hazards and long-term exposure to environmental toxicants occurring in concentrations too low to produce acute poisoning; interactions between different toxicants, changed patterns of morbidity and mortality; increased awareness and fear in the general population of environmental health hazards.

4) Change of legal responsibilities: Need for criteria and standard for measuring environmental quality; need for scientific basic knowledge to be able to set up standards; social and economical considerations of the "risk benefit analysis".

At the moment it can be difficult to determine which of the numerous environmental toxicants should be given the highest priority. Compounds showing increasing environmental concentrations with the ability of bioaccumulation and of known hazard to human health should be regarded as high priority chemicals. This applies to heavy metals such as mercury, lead and cadmium.

Biological monitoring of human exposure to heavy metals has regularly been carried out in Greenland since 1979. The background for initiating these surveys was the fact that analyses of meat and organs from marine mammals and fish caught along the Greenlandic coastline have shown concentrations of heavy metals (Hg and Cd) which according
to dietary calculations could give rise to a human exposure in excess of the WHO provisional tolerable weekly intake. Lead concentrations in food animals were, however, low and would not provide an excess exposure (Johansen, 1982).

As a consequence of the supposed high intake of mercury and cadmium, human surveys were started with collection of blood and hair samples from various districts in the country (Fig. 1). At the moment samples are collected from a total of approx. 1300 individuals corresponding to 2.7% of the total population. Table 1 summarizes the various subprogrammes carried out so far.

Fig. 1. Map of Greenland with indication of sampling areas.
### Table 1. Subprogrammes carried out in the period 1979-1985.

<table>
<thead>
<tr>
<th>Sampling place</th>
<th>District</th>
<th>Year of sampling</th>
<th>No. of samples</th>
<th>Sex</th>
<th>Analyses</th>
<th>Published</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>West Greenland</strong></td>
<td>Upernavik</td>
<td>1979</td>
<td>111</td>
<td>M</td>
<td></td>
<td>(1)</td>
</tr>
<tr>
<td></td>
<td>Umanak</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Godthåb</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Julianehåb</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>East Greenland</strong></td>
<td>Angmagssalik</td>
<td>1981</td>
<td>178</td>
<td>M+F</td>
<td></td>
<td>(2,3,4,5)</td>
</tr>
<tr>
<td><strong>Denmark</strong></td>
<td>Copenhagen*</td>
<td>1981</td>
<td>29</td>
<td>M+F</td>
<td></td>
<td>(3,6)</td>
</tr>
<tr>
<td><strong>West- and East Greenland</strong></td>
<td>Upernavik</td>
<td>1982</td>
<td>98x2</td>
<td>M+F</td>
<td></td>
<td>(7)</td>
</tr>
<tr>
<td></td>
<td>Umanak</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Angmagssalik</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>North Greenland</strong></td>
<td>Thule</td>
<td>1983</td>
<td>97</td>
<td>M+F</td>
<td></td>
<td>(8)</td>
</tr>
<tr>
<td><strong>North, East and West Greenland</strong></td>
<td>Godthåb</td>
<td>1984/85</td>
<td>357x2</td>
<td>M+F</td>
<td></td>
<td>(9)</td>
</tr>
<tr>
<td></td>
<td>Upernavik</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Umanak</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Thule</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Angmagssalik</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td>1325</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Eskimos living in Denmark.*

1) Hansen, 1981
2) Hansen et al., 1983a
3) Hansen et al., 1983b
4) Hansen et al., 1984a
5) Wulf et al., 1985
6) Hansen et al., 1985
7) Hansen et al., 1984b
8) Hansen & Sloth Pedersen, 1985
9) (unpublished)
Lead was also included in the programme in spite of the fact that it was not supposed to be of any importance, but as a consequence of ongoing surveys within the EEC at the time, surveys made according to the Directive of 29/3-1977 regarding the risk of lead exposure in the non-occupationally exposed part of the population. It was supposed that background material from a remote area could be provided in this way without any of the primary lead pollution sources i.e. motor-cars and industries. Selenium, an essential micronutrient, was afterwards included, as in animal experiments it has been proven as a powerful antagonist to toxic effects of mercury and cadmium.

An estimation of the historical development has been made possible by comparing concentrations in contemporary hair samples with samples from 8 15th century mummies found in West Greenland and from 4 samples collected in East Greenland, Angmagssalik district, in 1882 by the first expedition to these areas.

Validity of blood and hair as index of exposure

An index medium is a tissue, body fluid or excreta whose concentration of a toxicant reflects the body burden. Regarding mercury blood as well as hair has proven good indices (Hansen, 1981). Recent Sherlock et al. (1984) has reported the relationship between intake and blood concentration to be expressed by the equation:

\[
\text{Blood Hg (\mu g/l)} = 0.8 \cdot \text{daily intake (\mu g)}
\]
The hair/blood ratio is around 250 (Hansen, 1981). Lead exposure is also generally accepted to be reflected in the blood concentration, and consequently, blood samples were accepted as index in the EEC survey. Hair lead has been reported to be an exposure index, but in the Greenlandic survey it was concluded that blood lead was the index of choice. The blood cadmium concentrations are considered an expression of recent exposure and not of body burden. In a case where the exposure is practically constant it might nevertheless serve as a useful tool for the estimation of the exposure level. Like for lead the value of hair concentrations of cadmium as index is dubious. Blood selenium concentrations are reported to reflect daily intake while information on hair selenium is scarce. Results from the surveys among Eskimos do not indicate hair selenium to be very informative.

Under the conditions prevailing in Greenland with a supposedly rather constant exposure level of the elements under investigation blood seems a reasonable index of actual exposure. Hair concentrations will, however, even if not applicable on an individual basis on group basis provide some information on changing exposure levels.

The actual exposure level

Mercury

In agreement with what was expected the mercury concentrations found in blood and hair were high and furthermore
closely related to eating habits, i.e. how much local food consisting of meat of marine mammals was part of the daily diet. This is illustrated in fig. 2., which also demonstrates geographical variation in mercury exposure with a north-south declining tendency, reflecting the degree of technological development in the country. In the far north traditional hunting is still the main trade resulting in a high per capita consumption of local products while in the south modern technology and industrialization is dominant and will influence people, especially the younger generation towards a "western" life style, resulting in an increased consumption of imported food.

Fig. 2. Mean blood concentrations in relation to eating habits from various sampling districts.
Based on the well established daily intake blood mercury relationship (Sherlock et al., 1984) and the median blood concentrations found in the different regions an estimation of actual weekly intake can be made. This is illustrated in table 2, which also shows that the WHO provisional tolerable weekly intake of mercury (as methyl mercury) of 200 μg/week can be exceeded by a factor as high as 8.3.

WHO has indicated a blood concentration of 200 μg/l as the lower limit for appearance of unspecific signs of toxic effect in adults. This concentration was found exceeded by 16% of the investigated adult population in North Greenland (Thule) the highest concentration recorded was 267 μg/l. Specific signs of intoxication will, according to Junghans (1983), appear of blood concentration ≥1000 μg/l. So, in general there seems to be no immediate risk to the adult population. As, however, methyl mercury passes the placental barrier and fetal tissues are supposed to be more sensitive to toxicants than are the mature maternal tissues the real problem in the actual mercury exposure among the Eskimo hunting populations is exposure in utero. At the moment cord blood samples are continuously collected and analysed from 6 districts.

Table 2. Estimated weekly intake of methyl mercury in different regions in Greenland.

<table>
<thead>
<tr>
<th>Region</th>
<th>Estimated weekly intake (μg)</th>
<th>Estimated PTWI</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Extreme intake</td>
</tr>
<tr>
<td>North</td>
<td>896</td>
<td>1666</td>
</tr>
<tr>
<td>North West</td>
<td>343</td>
<td>546</td>
</tr>
<tr>
<td>South West</td>
<td>175</td>
<td>248</td>
</tr>
<tr>
<td>East</td>
<td>392</td>
<td>476</td>
</tr>
</tbody>
</table>
Cadmium

The next metal of concern with regard to a high daily intake through the Eskimo diet is cadmium. Johansen (1982) has calculated a weekly intake as high as 5 mg/person as the highest exposure level. This figure corresponds to 10-12.5 times the WHO provisionally tolerable weekly intake of 0.4-0.5 mg/week.

Blood cadmium concentrations from the investigations in west and east Greenlandic districts showed, however, no influence from eating habits, smoking being the only determining factor to the blood level. As for mercury the highest exposure level should be expected in North Greenland and in fact in that study (Hansen & Sloth Pedersen, 1985) not only smoking but also eating habits were found to be reflected in the blood cadmium level as shown in fig.3. Smoking is, however, still the most important factor.

**Fig. 3.** Blood cadmium concentrations from North Greenland in relation to eating and smoking habits. Geometric mean and 2 x SEM indicated (Data from Hansen & Sloth Pedersen, 1985).
It is concluded from the blood cadmium data that smoking is the most important factor for cadmium exposure in Greenland just as it is the rest of the world. Dietary cadmium as found in Eskimo diets is presumably not easily absorbed and is only moderate reflected in blood cadmium concentrations, and only on a very high intake level.

An estimation of dietary intake cannot be made on a basis of blood concentrations. Partly because no relationship has been established and partly because the exposure occurs from several sources. Preliminary results from a food survey have given median concentrations of cadmium in meat and organs from various food animals. By applying this to known information on daily intakes of local food items a rough estimate of weekly intakes of cadmium can be made as shown in table 3.

Table 3. Estimate of weekly dietary intake of cadmium in various geographical regions in Greenland.

<table>
<thead>
<tr>
<th>Regions</th>
<th>Estimated weekly intake µg</th>
<th>Estimated PTWI</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Extreme exposure</td>
</tr>
<tr>
<td>North</td>
<td>2583</td>
<td>4802</td>
</tr>
<tr>
<td>North West</td>
<td>987</td>
<td>2296</td>
</tr>
<tr>
<td>South West</td>
<td>483</td>
<td>693</td>
</tr>
<tr>
<td>East</td>
<td>1134</td>
<td>1365</td>
</tr>
</tbody>
</table>

Like for mercury it is seen that the dietary cadmium intake in Greenland supposed exceeds the WHO PTWI with a factor ranging from 1-12. The smoking exposure seems, however, more
important to the blood cadmium level, and further investigations of the absorption of cadmium from natural bindings in foodstuffs are highly needed to determine hazards of dietary cadmium.

**Lead**

The lead burden in Greenland was supposed to be low due to the absence of the most important environmental sources, car traffic and industries as well as low concentrations found in food. Surprisingly the blood lead level found in West as well as in East Greenland was on the same level as the one found in European industrialized countries.

Median concentrations ranged from 8 µg/100 ml in the Thule district to 16 µg/100 ml in Angmagssalik in East Greenland. In fig. 4 is shown the results from East Greenland where 4 samples exceeded the 35 µg/100 ml fixed within the EEC as the upper acceptable blood lead concentration in non-occupationally exposed persons.

The reason for this relatively high blood lead level has not been revealed as no relationships to eating habits have been found, neither could the high alcohol consumption give a satisfactory explanation, but this is probably a significant cofactor. It is possible that dietary factors such as low calcium and high protein and iron intake which are characteristics of the Eskimo diet favour intestinal lead absorption.
Selenium

Blood selenium concentrations have been determined in two districts, Angmagssalik and Thule. The concentration level was high compared to European countries, but very different in the two districts with median concentrations of 130 \( \mu g/l \) and 1225 \( \mu g/l \), respectively. These various differences cannot be explained, but are probably a result of interspecies variations among food animal and of different eating patterns in the two districts. A close relationship between blood selenium concentrations and eating local food was noticed.
On a molar basis selenium was found—in surplus to mercury in human blood, which according to animal experiments should provide a maximum protection against toxicity of mercury and cadmium. To draw this conclusion might, however, be rash as laboratory conditions very seldom reflect the natural exposure. Our finding in the Angmagssalik material demonstrated that the frequencies of sister chromatid exchanges could be significantly related to blood mercury and blood cadmium concentrations, while no influence by selenium could be revealed. For this reason we feel that the actual exposure level among Greenlandic Eskimos should be regarded as a serious problem.

The historical perspective

The finding in 1978 of 8 well preserved mummies in Qilakitsoq in West Greenland dated by the C¹⁴ method to 1475 ± 50 years, made it possible through hair analyses compared to analyses of present day samples to obtain an idea of the metal status in an ancient population living entirely of local food. As the mummies were dressed in sealskin furs it was possible to analyse and compare animal hairs. The relative concentrations in ancient and present day Greenlandic hair samples are given in fig. 5, where the concentrations in ancient hair are 1. The figure shows mercury and lead which have increased by time in human as well as in animal samples, while cadmium was only found to have increased in animal hairs. The arithmetic means are shown in fig.
Fig. 5. Relative metal concentrations in ancient and present-day Greenlandic hair samples.

Fig. 6. Metal concentrations in Greenlandic hair samples from the 15th, 19th and 20th century.
where the incorporated results of analyses of 4 19th century samples collected in Angmagssalik in 1882 are also found. The figure also includes the essential microelement selenium. It was surprising to find that mercury, cadmium and selenium in the 19th century samples were lower than those in both 15th century and 20th century samples. As these elements are supplied through the diet the low concentrations can be explained through the fact that the East Greenlandic Eskimo during the 1880 suffered from severe famine.

The finding that lead concentrations in the 19th century samples were higher than those in the 15th century samples and on a level comparable to the 20th century samples supports the idea that lead exposure in Greenland is not primarily of dietary origin even if dietary factors probably enhance the absorption. Furthermore it should be noticed that selenium concentration was highest in the 15th century samples. The same tendency has been found to be true also for iron and bromine. The phenomenon is obviously a result of the fact that life style is changing from the local food towards an increasing influence of western imported food.

Sources of heavy metals in the arctic environment

The toxic heavy metals are ubiquitous and have always been present in man's environment in natural background concentrations. These may vary according to geographical conditions, as well as time related fluctuations may occur. Con-
sequently it is difficult to distinguish between background or natural concentrations and the contribution by man-made pollution.

Evidence from the mercury analysis indicates that an increased input in the marine environment has taken place by time corresponding to the increased technological use of this metal. The increase in cadmium concentrations in seal hair is also an indication of a beginning marine pollution of this metal, which contrary to mercury and lead has only been used in this century. Lead is the element which has shown the biggest relative increase. This is in agreement with the viewpoint made by several authors that environmental lead concentrations have increased steadily in the northern hemisphere in historical time. Rahn & McCaffrey (1980) have demonstrated long distance atmospheric transport of pollutants from the industrialized zones in Asia, Europe, and U.S.A. to the arctic areas. A long distance transport of airborne lead particles would agree with our findings that lead is present in the arctic environment and gives rise to relatively high human blood concentrations, while there is no support for the idea of a dietary exposure. The actual transfer pathway of lead to man remains, however, to be revealed.

All surveys carried out in the country until now show an impact of heavy metals on man and environment with origin in a general environmental pollution, as no relationship or influence on local technical activities e.g. mining so far has been seen.
The general picture is that to-day from being a remote isolated area Greenland has become a part of the rapidly developing western technological society. This implies progress of the Greenlandic society but also partaking in the problems created by pollution. The specific living conditions still prevailing in Greenland make the Eskimo population very vulnerable to adverse effects of environmental toxicants; therefore a very careful medical supervision as well as implementation of legal guidelines are highly needed to protect the Eskimo culture in the future.
References


Greenland Telecom is a department of the Greenland Technical Organisation (GTO), and is in charge of telecommunications in Greenland and between Greenland and the rest of the world. GT's staff number about 500, of which 100 are employed in Copenhagen, and 400 by the telecommunication districts in Greenland. About 250 of the staff are of Greenlandic descent, whereas the rest have been called in from Denmark. GT's annual turnover amounts to about 200 mill. Dkr.

GT runs the Public Telecommunication Services in Greenland. They are, for example, the -

- telephone service
- telegram service
- telex service
- data communication service
- coast radio service.

All these services are affiliated to the international telecommunications network, and communication is possible from Greenland to the whole world.

This means that telephone communication can be established from all towns in Greenland and from most settlements to all parts of the globe. Today it is possible to call Denmark on International Subscriber Dialling, and in a few months it will be possible to dial many other countries as well. The limitations
are set by the international network, not by the network in Greenland.

This also applies to the telex and telegram services, and to a new data network, which will be put into service in 1986.

The present modern telecommunications network in Greenland has been developed over the last 20 years. Greenland Telecom began its activities in 1925 by establishing the first radiotelegraph stations. So this year we are able to celebrate GT's 60th anniversary. The radiotelegraph was the most important way of telecommunication until the mid-60s, when we began establishing telephone systems in the towns. From 1970 we began the establishment of micro-wave radio-link systems and systems of communication by satellite, and they now bind Greenland's inhabited places together into a network, and connect Greenland with the rest of the world.

It is true that Greenland is a large country geographically, but the population is small, 50,000 inhabitants. Therefore Greenland Telecom is, of course, a telecommunications company of modest dimensions with our 13,000 subscribers. On the other hand I suppose we are one of the most expensive, as you may have noticed when using our telephones.

This is due to the enormous geographical extent of the areas we have to cover, and of course the sparsity of the population.
Figure 1 shows a map of Greenland with indication of the most important parts of the country's telecommunications network.

The West Coast towns are connected by a micro-wave radio link, the total length of which is about 1,500 km. The other towns are connected by a satellite communications system which we call INUKSAT, utilizing a satellite run by INTELSAT. The towns in question are Qaanaaq (Thule), Upernavik, Ittoqqortoormiit, and Ammassalik, which are connected by satellite to earth stations at Nuuk and Aasiaat, and are thereby included in Greenland's telecommunications network. By INUKSAT Greenland is connected to Denmark, and consequently to the rest of the world. Settlements and other inhabited places are connected to the network by smaller radio links.

Apart from public services, Greenland Telecom runs a number of separate services for various organisations and authorities. The services are, for example:

- search and rescue services for ships and planes,
- weather stations for the Danish Meteorological Institute and the International Civil Aviation Organisation, ICAO,
- radio beacons for ships and planes,
- navigation and communication equipment in airports,
- broadcasting networks for the Greenland Broadcasting Service (KNR).
I shall describe some of our activities which may be of special interest to POAC participants.

1. The mining company GREENEX, which is present at this conference, have normal services such as telephone and telex at their disposal by means of a radio link. Add to this the KNR radio programme and the possibility of connecting data equipment. We try hard to maintain a reliable service of reasonable quality, and we succeed most of the time.

2. The oil company ARCO, which operates in Jameson Land, is served in the same way by a radio link from Ittoqqortoormiit to Constable Point. The connection will be put into operation next week. GT is also in charge of the installation and maintenance of communication and navigation equipment in connection with the Jameson Land airstrip and traffic by sea. ARCO's back-up system is an earth station connected to the International Maritime Satellite Communications System INMARSAT.

3. Danmarkshavn, which is a weather station situated in a deserted area 700 km north of Jameson Land, is run by GT on behalf of ICAO, and is also connected to the international telecommunications network by an INMARSAT terminal. The weather station is of great importance to the weather forecasts for civil aviation across the North Atlantic Ocean and the North Pole region.
4. Other firms and institutions are served by GT's coast radio service on MF, HF, and VHF, or through special radio circuits.

5. The search and rescue services for ships and planes are also of considerable importance to firms and institutions operating in Greenland and in Greenland waters.

6. A special search and rescue system that is under development is the COSPAS/SARSAT system. This is a satellite-based system which can pick up signals from emergency transmitters in ships and planes, determine the position of the transmitters with great exactitude (5-10 km), and inform rescue centres of the position. The system is in the experimental phase, and is operated by the United States, Canada, France, and the Soviet Union in cooperation. GT takes an active part in the Danish pilot programme that is attached to the system. In several cases the system has been utilized with success in rescue operations in Greenland.

It may sound as if we are both proud and somewhat boastful. But still, Greenland Telecom can offer a large number of services, through our own resources, or in cooperation with the Danish Post and Telegraph Company as well as international organisations such as INTELSAT and INMARSAT. It's expensive, okay, but we can make it work.
I shall briefly mention some of the special technical challenges which Greenland Telecom has met in its work.

Part of the radio-link connections between the towns and settlements in Greenland are a great number (about 30) of repeater stations in deserted places and often on mountain tops, at altitudes of up to 1,500 m above sea level.

Equipment and staff are normally transported by helicopter. Our own staff build up the plant on location with masts, buildings, and installations – however, pre-fabricated units are employed to some extent. The plants must be able to withstand great wind loads and low temperatures. In order to achieve a high degree of dependability, we use very reliable equipment, usually doubled, automatically supervised, and operated from one of our manned centres.

The staff employed for the maintenance and repair work are brought to unmanned telecommunications plants by ship if possible, otherwise by helicopter, and in a few cases by dog sledge. However, in order to establish and operate large parts of the telecommunications network, the use of helicopters has been an essential condition. Therefore we are one of Greenlandair's good customers, and there is always a helicopter at our disposal.

Electricity is supplied to our plants and installations in the towns, and wherever possible by the pub-
lic network. In all other cases GT establishes its own electricity supply for its plants. Particularly at the repeater stations in deserted areas, great efforts have been made in developing and testing plants that are reliable and at the same time economical. As a main source of supply we use diesel generators, thermoelectric generators run by gas, windmills, or solar cells, normally in connection with a chargeable battery. Add to this non-chargeable batteries used as spare plants and a diesel plant used during maintenance calls to the station.

When dimensioning the micro-wave radio link we have chosen equipment with a very low energy consumption. A repeater station on the radio link will therefore have a normal power consumption of 40-50 W, corresponding to that of an electric bulb. Therefore it is necessary to have a special diesel generator to supply power for lighting, instruments and tools when the maintenance crew are there.

The electricity supply is a weak point in the radio-link network, and GT therefore works at the improvement of the plants and their supervision and control.

We have another problem which today may be of moderate extent, but which, nevertheless, causes irritation and often damage to our plants. The problem is wanton destruction. Mostly in the form where some of our plants seem to be attractive targets for practising rifle shooters. When essential parts of the antenna and cable systems are hit and damaged, the
operational and economic consequences may be very serious. GT seeks to discourage wanton destruction through films and information, which have had a positive effect.

One of the areas of technology that GT follows closely is that of satellite communication. In that area there is a tendency towards the use of small earth stations, which makes it possible to establish communication with positions with limited traffic needs, and to do so in a way that is financially reasonable. Systems of that kind are known today from the maritime field (INMARSAT), and now they are also offered for other purposes. This makes it possible to establish satellite communication to positions with a single or few telephone channels.

This is of interest in two ways: In connection with the extension of the telecommunications network to many settlements in Greenland with a small population, where the telephone service is not satisfactory, and in connection with the supply of telecommunication services to such activities as those relevant to this conference, and which often take place far from the public network of the inhabited places.
1 ABSTRACT

In planning the future energy supply situation of Ilulissat a solution based on hydro power has shown favorable. In 1976 field investigations were initiated and since 1981 these have been intensified along with designing and feasibility study. After a brief presentation of the project and the investigations, focus is put on the permafrost conditions which are of major importance with respect to necessary field investigations, plant design and future operation. Knowledge of systems under such conditions is very sparse throughout the western hemisphere.

2 INTRODUCTION

The idea of exploiting hydraulic power for the production of electricity for Ilulissat is about ten years old. At that time thoughts of utilizing the volumes of water in the fiord north of Ilulissat, Paakitsup Ilorlia, emerged. At first there were plans of a tidal power plant, but they were soon abandoned on account of the relatively modest tidal variation combined with the rather delicate technique required. From Figure 1 it can be seen that a number of reconnaissance trips have been made where such factors as distance to Ilulissat combined with topography and accessible water volume have decided which areas were of interest. On the map, Figure 1, a number of basins have been drawn, and it appears that the nearest ones are good on account of the short distance to Ilulissat, but characteristic for these areas is the low annual precipitation of 200-300 mm; this means that rather large precipitation areas would be required - and they are not available
here - so resort must be to the melting of the inland ice.

An offshoot of the tidal power project was a damming up of the entire fiord, but this project too was shelved on account of the fairly extensive dam building with heights of up to 50 m or so, combined with the fact that a period of some eight years would elapse before there would be water behind the dam. It was not very attractive economically.

The result of all the reconnaissance work was that an examination of the area near Paakitsup Akuliarusua was started in 1980-81. The project found on the drawing table today is shown in Figure 2, where you see the three lakes "233", "187" and "326", the inland ice, the natural run-off pattern as well as the recommended tunnels, with separate head-race tunnels from "233" and "187" to a joint power station plus a tail-race tunnel into the fiord. Lake "326" has a run-off pattern which is unknown for the present, and based on various deliberations, the idea of including the lake in the project has been abandoned for the time being; possibly a regulation may have to be made at intervals of several years. The dam shown on the map is intended for a possible future extension, and is therefore not part of the present project.

3 PROBLEMS

In this particular area there are special problems with respect to the utilization of the "white oil", as a combination of cold melt water from the inland ice and permafrost in the mountains is found here. It is a rather specific problem which has been discussed earlier in connection with Marmorilik, but so far
we have been unable to gain experience or find solutions to this problem. On these grounds some studies have been made in the field, and they have led to calculations and the setting up of a model.

Looking at the in-flow to lake "233", it is discovered that there are not directly glaciers in the lake, and this means that the water for the lake passes bare ground for a while before reaching the lake. Conversely, a glacier is placed directly in lake "187", with melting in the lake. This manifests itself in differences of temperature, so that the temperature in lake "233" is significantly higher (about half a degree C) than the temperature in lake "187" both winter and summer. In the same way the topography shows that the rock, overlaying the tunnel between lake "233" and the power station is somewhat thicker than the case at lake "187". Thus it is expected that the rock temperature is not lower, at any rate, from lake "233", and on account of all this we have concentrated our efforts on finding a solution with the cold water from lake "187", through the tunnel and out into the fiord. If this problem has been solved, lake "233" could be selected according to this solution with a reasonable degree of certainty.

4 THE ROCK

The cross section of Figure 3 indicates the influences on the surface; exchange of energy in the form of precipitation and evaporation, convection in connection with wind, solar radiation, long-wave radiation - also topography and exposure are of importance. If you look down through the profile, you will first encounter the active layer which thaws and freezes, then follows a layer which may be frozen, but which
does have a certain variation of temperature on account of its position near the surface, and next there is a layer with negative temperatures which will change into an area with positive temperatures - somewhere down there.

If rock is regarded as a material, the interesting parameters in this context are the thermal conductivity, the specific heat and the content of ice, water and air.

In this connection the active layer and the one which is influenced by the surface are not particularly interesting. Of greater interest is the layer with negative/positive temperatures. Material parameters like conductivity and capacity are subject to a variation in the rock, and consequently these need to be known in some more detail. The content of ice, water and air are of importance for special energy exchanges in the form of latent energy during phase changes.

5 THE WATER

The water from the lake is subject to a similar influence from the outside wind, radiation and water balance. The interesting things about the water are the temperature distribution, the fluctuation over the year, the specific heat, the salt content (salinity), if any, the thermal conductivity, the latent energy, and the content of suspended material. Figure 7 shows, that a temperature of +4°C is never reached, so constantly there is a heavy current (warm water) to the bottom, and the otherwise well-known phenomenon of change in temperature profile will not occur. Figure 4a shows the temperature of max. density and Figure 4b shows partly the max. density temperature as a function
of the salinity, partly the freezing point as a function of the salinity. Figure 4c shows a rather interesting thing, namely the lowering of the freezing point as a function of the pressure, and from this it can be seen that when the pressure increases by one bar (abt. 10 m water column), the freezing point is lowered by approx. one seventhousandth of a degree.

6 THE WATERWAYS

In studying a stylized cross section with lake, tunnels in frost and a fiord, Figure 5, problems is expected with respect to intakt, surge gallery, compressed-air chambers and the like, due to the supercooled water and poor circulation. The pressure drop through the turbine brings about a considerable increase of the freezing point, and finally there is the effluent which creates some brackish water in the fiord. The processes to be considered are friction, convection, latent energy exchange, and energy loss in the water in the form of dissipation. Any formation of ice will create the possibility of ice break-up through pressure surges, and maybe damage to the turbines.

7 FIELD INVESTIGATIONS

The exact position of the permafrost line has not been determined yet, but the dependence on the fluctuating temperatures of the rock and on the water temperature are important parameters here. In Figure 6 is shown the location of measured temperature profiles in lake and fiord, named TP, and of temperature profiles in the underground, named K and T. The K profiles
are interesting deep profiles, whilst the T profiles are surface temperature stations down to a depth of 3 m which give you an idea of the importance of exposure. Figure 6 furthermore depicts three automatic stations, AT, which record the run-off and the temperatures at the bottom of the lake every third hour.

Figure 7 shows two temperature profiles from lake "187", a typical winter profile and a typical summer profile. It will be seen that the winter profile is very close to zero, with a slightly warmer part at the bottom.

The salinity of the lake may be considered as being zero, and in the same way the content of suspended material is so negligible that one cannot expect to see a lowering of the freezing point of any size worth mentioning.

We are therefore concerned with water hovering around the freezing point, but water nevertheless of +0°C. A similar profile in front of the glacier shows the same conditions, but slightly lower temperatures. This has the effect, however, that there may be weak horizontal density currents under the ice cover during the winter.

In the summer the temperature is just below +2°C, and the distribution is rather even. This is due to the very strong effect of the winds in the area and the everlasting mixing of surface water that sinks to the bottom on account of the density; the lake presents a full mix-up of its waters.

In the fiord there is a layer of brackish water with summer plus-temperatures down to a depth of 20 m, and in the winter there is an upper layer of approx. 10 m with a temperature of -1°C, followed by an intermediate layer down to a depth of 15 m to which the
summer heat is slowly squeezed down.

All these things are relatively well-known arctic-glacial influenced lake phenomena.

If you look at the drill holes, you will see that a rather extensive drilling programme has been carried out in order to obtain some rock-mechanical parameters, to make some tests, to log the rock to discover its structure and build-up, but also to lower temperaure detectors into them. Figure 8 shows such a vertical drilled hole and the temperatures the day the detectors were put down, and the temperature dominance of the drilling water is seen with all possible clarity. One can furthermore see the change in the course of three weeks, and the gradient is roughly 1.6 degrees per 100 m. Similar registrations are found for other drill holes. Figure 9 shows the temperature drop from the time of establishment and three weeks on, recorded once per day, and you will note a certain standstill around 0°C, where ice formation and release of latent energy take place, but otherwise the temperatures are dropping gradually, and no quick stabilization should be expected.

On core samples the thermal conductivity has furthermore been measured, and it turned out to be surprisingly low which has given rise to doubts concerning the assumption of homogenous and isotropic conditions.

8 MODEL WORK

The purpose of this data-collection stage is to set up a dynamic model where different operating situations can be simulated. For this purpose a two-dimensional, stationaty model has been made, and Figure 10 shows
its cross section divided up into several boxes. It is however a question whether the two singular points, partly at lake "187" and partly at the fiord, are in fact singular points, but this has been assumed. The temperatures found have been put in as boundary conditions, and the model has been tested for the solution of La Place’s equation assuming identical thermal conductivity and specific heat. The result is shown in Figure 10, and here you will note that the zero isotherm is placed rather deep.

Agreement with the measurements made in the drilling holes is quite good. The result is that the tunnel should be positioned so that the smallest possible part of it is placed in the completely frozen areas. In other words, one should let the tunnel dive very quickly with a shaft under the lake, and then let it level out at around elevation 0. A low manning figure will help a little on the friction, and hence on the temperature, and this will reduce the demands to the contractor’s work. A tunnel cross section of 7 m² and a water flow of 3.5 m³ per second will give a water velocity of half a metre per second. A 7 m² cross section assumes a small inclination of the tunnels (track-bound material), whereas tunnels with a little more inclination (for vehicles with rubber wheels) with a larger min. cross section will give a lower velocity.

Now, if you would like to study some interesting situations, you should partly look at start-up, smooth operation both summer and winter, short close-downs to ensure the most economic production, partly on close-downs due to breakdowns or necessary overhaul of the equipment. This is where the dynamic operation simulation model comes into the picture. Figure 11 shows the cross section again with the temperature distribution in the mountain as well as three different tunnel positions, partly a high-lying horizontal one with a sloping shaft and long tailrace tunnel, similarly a high-
lying tunnel with some inclination (25 o/oo), and finally a case with a vertical shaft and an evenly sloping tunnel in the direction of the fiord. With this system we have run a model with a distribution of the water temperature in the lake and a distribution in the mountain. The model calculates the temperature distribution and the heat flow to the mountain, and subsequently computes the return temperature of water passed on to the next step, which means that we obtain a calculation procedure where the temperature distribution to the mountain is calculated all the time. Similarly we obtain a calculation of the water temperature at the axis of the tunnel, and the critical areas will typically be horizontal sections where a lowering of the freezing point created by increased pressure will not be present. Figure 11 shows one of the selected critical points, just before the vertical shaft of the selected critical points, just before the vertical shaft dives, and in Figure 11 you can see the fluctuation of the lake's temperature, among other things. During the first year or so, 1.5°C, which is caused by the heat added to the tunnel wall on account of the building activities, an artificial heating process, in other words. Figure 11 furthermore shows the variation of the freezing point isotherm, and you will note that it starts following the lake temperature surprisingly fast; the isotherm moves right down to the wall in this case. The water temperature does not however sink significantly by the water running through the system, but in the winter the great pressure release after the turbine is critical, as the water temperature is around 0°C. Ice formation and blocking of the tailrace tunnel may occur, but it is quite feasible to use the residual heat from the system, so that you cool the generator and transformer with water from the turbine and then lead it back to the outlet water, whereby heating of the outlet water is obtained in surplus of the turbine loss.
In conclusion it may be said that such an installation must be started up in the summer in order to build up as much heat as possible in the rock, before the water temperature starts falling.

The location and operating strategy of the station will furthermore depend on whether ice is accepted in the tunnel. By making use of the two different lakes in turn, the situation is that of "stagnant tunnels", whereas a coordination of them will result in a complicated operating strategy. If ice is accepted the next question is how much and this has to do with the danger of ice break-up through pressure surges, possibly ice drift through the turbine and complete blocking of the turbine. For pressure equalization purposes by-pass valves may be installed, because the system will be vulnerable to frost problems, if a low-lying tunnel with an air pressure chamber is chosen. Finally there is the possibility of incorporating a by-pass in such a way that the water will always be kept moving, also when repairing the system or give it a check-up. Every cubic metre of water circumventing the turbine will however in principle represent an economic loss.

9 ECONOMY

Compared to present energy supply systems, the project is good business. The way things look at present the capital expenditure will come to 400 million kroner, or roughly 5 Dkr. per produced annual kilowatt hour, or a rounded production price, about 50 øre per produced kilowatt hour. The preliminary studies carried out so far have cost about to 9 million Dkr.
10 CONCLUSION

Through this project we have obtained a very good knowledge of the problems, the way they probably are, and a good knowledge of methods, equipment and studies, and how they are carried out in practice. Our knowledge of the processes has been increased considerable, partly thorough the investigations in the field, and partly through the work with the model, so the old well-known permafrost map of Greenland probably will not be sufficient for projects of this nature in future. It is not enough just to check the air temperature and the latitude.

Worldwide there is a growing interest in cold areas, and in China, the Soviet Union, Canada and Alaska, for instance, they move further and further to the north, build installations, study resources and their utilization. Here, too, the technology in these studies will play an important role in the coming years, so the Ilulissat hydro power scheme is clearly a specific project with great perspectives.
FIGUR NR. 2

NATURAL WATERCOURSE
POWER STATION
TUNNEL
DAM SITE FOR FUTURE DEVELOPMENT
EVAPORATION  RADIATION

PRECIPITATION

TOPOGRAPHY/EXPOSURE

WIND

THERMAL CONDUCTIVITY

HEAT CAPACITY

GEOTHERMAL GRADIENT

ICE/WATER/AIR CONTENT

ACTIVE LAYER

AFFECTED FROM SURFACE

NEGATIVE TEMPERATURE

POSITIVE TEMPERATURE

FIGUR NR.3
THERMAL CONDUCTIVITY, WATER $\sim 0.1 \text{cal}/\text{M} \cdot \text{S} \cdot ^\circ \text{C} (0.4 \text{W}/\text{m} \cdot ^\circ \text{C})$

HEAT CAPACITY, WATER $\sim 1 \text{cal}/\text{g} \cdot ^\circ \text{C} (4.2 \text{kJ}/\text{kg} \cdot ^\circ \text{C})$

THERMAL CONDUCTIVITY, ICE $\sim 0.5 \text{cal}/\text{g} \cdot ^\circ \text{C} (2.1 \text{kJ}/\text{kg} \cdot ^\circ \text{C})$

LATENT HEAT $\sim 80 \text{cal}/\text{g} (334 \text{kJ}/\text{kg})$
TEMP [°C]

FIGUR NR. 9

Temperaturmålinger, august 85
K 85904 (kote 149,1). Etableret 07.08.85
Skrå dybde 228 m; lodret dybde 169 m.
CROSS SECTION IN TWO DIMENSIONAL MODEL

DIVISION INTO ELEMENTS FOR MODEL CALCULATIONS

STATIONARY MODEL - ISOOTHERMALS IN °C

FIGUR NR. 10
LONG CALVING WAVES

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ABSTRACT

When icebergs are calved from a large glacier, different kinds of waves are generated in the waters adjacent to the glacier front. Some of these waves may travel long distances, still being detectable and even causing trouble tens of kilometres from the site where they were generated.

A well-known example is the seiche-phenomenon called "kaneling" which occurs in the harbour bay of Jakobshavn, West Greenland and is caused by calvings from Jakobshavn Isbrae, the big outlet glacier from the Greenland Ice Sheet, situated some 50 km east of the town of Jakobshavn.

However, far-travelling calving waves have been reported also for other locations in Greenland. A review is given of these observations.

The theory of long calving waves is briefly discussed. The velocity of propagation of the waves can be determined by the theory of long gravity waves in channels. Expressions are deduced for the height and frequency of waves generated by the oscillatory motion of icebergs detached at a calving. The main results of the older theory of long periodic calving waves generated by the oscillatory motion of the glacier itself (Reeh, 1970; Reeh and Engelund, 1971) are also reviewed.
When icebergs are detached from the front of a tidal glacier, different kinds of waves are generated. Some of these waves may travel long distances and still be detectable tens of kilometres from the site where they were generated. The waves are characterized by long wave lengths and seem to occur in Greenland in regions where large outlet glaciers from the ice sheet terminate with floating or nearly floating, calving fronts at the head of long narrow fjords. Two kinds of long calving waves have been observed: 1) surge waves produced by translatory motions of detached icebergs and 2) periodic waves originating from oscillatory motions of icebergs or floating glacier tongues.

REPORTS ON CALVING WAVES

Few descriptions of calving waves can be found in the literature. The reason is probably that glaciers capable of generating significant waves are, with a few exceptions, situated far from inhabited areas. In Greenland numerous large glaciers reach sea level. A few of these terminate rather close to settlements and calving waves have been reported for some of these glaciers. The most well known example is the so called "kaneling", a seiche-phenomenon occurring in the harbour bay of Jakobshavn, West Greenland, see map in figure 1. The "kaneling" which is described by e.g. Sørensen and Schröder (1971), denotes the more or less violent oscillations with a period of about 6 minutes of the water in the harbour bay of Jakobshavn which occur now and then, apparently without any cause, since at the same time the sea outside the harbour bay may appear completely calm. As early as 1893 Hammer (1893, p. 22) related the "kaneling" to the calving activity of Jakobshavn Isbræ, a large glacier terminating some 50 km east of Jakobshavn at the head of Jakobshavn Isfjord (figure 1).
Engelund (1957) supported and improved this explanation by stating that the harbour bay of Jakobshavn is very likely in resonance with long period calving waves generated at the terminus of Jakobshavn Isbrae. Later this hypothesis was further supported by a calculation of the natural frequency of the Jakobshavn glacier-fjord system (Reeh, 1971), indicating a period of the same order of magnitude as observed for the "kaneling".

Also in Umanak Bugt further to the north in West Greenland calving waves have been observed in Qaraqaq Isfjord and Karrat Isfjord (see map in figure 1).
These fjords are headed by the largest outlet glaciers in the area, Store Gletscher and Rink Isbøe respectively.

In Qarajaq Isfjord, calving waves have been observed during the Grønland-Expedition der Gesellschaft für Erdkunde zu Berlin 1891-1893 (Drygalski, 1897, p. 394-400). A total of 28 observations are recorded of which 20 with a large degree of certainty could be referred to calvings of Store Gletscher. In most cases the waves were recorded by the watergauge, installed at the expedition hut situated some 15 kilometres down-fjord from the glacier terminus. Drygalski describes the waves at this site as very long, with a period of several minutes and an amplitude of 2.5 metres or more. At Ikerasak, an outpost situated some 50 km from the glacier, the waves were still significant, particularly in the summer when the waves were not damped by the ice cover of the fjord.

In Karrat Isfjord calving waves have been observed by Sorge (1933, p.13-14) close to the front of Rink Isbøe. The height of the waves were measured to be 6-7 m at a location about 2 km from the glacier front. However, calving waves were observed as far away as 65 km from the glacier terminus. They are described by Sorge to have very long wave lengths. When meeting such waves in open water in a small boat, one had the impression of first sailing upslope for a while, and next downslope for a while.

In East Greenland calving waves have been observed in the narrow inner fjords of the Scoresby Sund fjord system and in Dove Bugt (see map in figure 1). Backlund (Koch, 1955 p. 346-348) experienced calving waves generated by Daugaard-Jensen Gletscher at the head of Nordvestfjord under extremely dramatic circumstances. Backlund and his party, when camping close to the shoreline some 10 km from the terminus of Daugaard-Jensen Gletscher were waken up in the night by a violent breaker, which washed ashore their boat and left it 10 m above the high water mark. By a second and a third wave the boat was set
afloat again. Luckily one of the men had succeeded in getting aboard and drifted out of the bay. After several hours when the sea had again calmed down, man and boat returned - quite incomprehensibly unharmed. Backlund does not directly state the period of the waves but a lot of equipment was saved in between the arrivals of the waves which therefore probably had a period of some minutes.

During the Geological Survey of Greenland expeditions to central East Greenland in 1968 and 1972, glaciological investigations were carried out on the major outlet glaciers from the Greenland ice sheet, calving into the the Scoresby Sund fjord system (Olesen and Reeh, 1969; Henriksen, 1973). On these occasions calving waves were observed in Nordvestfjord and Føhnfjord, produced by calvings of Daugaard-Jensen Gletscher and Rolige Bræ, respectively.

Finally the observation of calving waves reported by Koch and Wegener (1930) should be mentioned. Also in this case observations were undertaken under the most dramatic circumstances. The party of Koch and Wegener camped on Storstrømmen glacier close to its terminus in Dove Bugt (see map in figure 1), when a large part of the glacier in the immediate neighbourhood of the camp site calved off. The accompanying wave which according to Koch's description probably was a large single wave, almost reached their tents elevated 15 metres above sea level.

In summary, it appears that all locations where long calving waves have been observed, are characterized as long, narrow fjords headed by major outlet glaciers. Thus long calving waves are to be expected also at other sites where similar conditions prevail.

THEORY OF LONG CALVING WAVES

Velocity of propagation, wave length and wave height.

The velocity of propagation of long calving waves
can be calculated approximately from the theory of long waves in channels as

\[ c = \sqrt{gD}, \]  

where \( g \) = acceleration of gravity and \( D \) = depth of the fjord.

Taking \( D = 500 \) m as a characteristic depth of a Greenland ice fjord one obtains a velocity of propagation of \( c = 70 \) m/s \( \sim 250 \) km/h.

The wave height can, to a first approximation, be calculated as follows:

If, at the head of a channel with water initially at rest, the discharge is suddenly changed by \( \Delta Q \), a water level increase of

\[ dy = \frac{\Delta Q}{Bc} = \frac{\Delta Q}{B\sqrt{gD}} \]  

(\( B \) = channel width) will start travelling along the channel with a velocity of propagation given by equation (1). Assuming \( B \) and \( D \) to be constant, equation (2) may be integrated to give \( y = Q/(B\sqrt{gD}) \).

From this expression the wave height which corresponds to the maximum value of \( Q \) is found to be

\[ H = Q_{max}/(B\sqrt{gD}). \]  

This expression is valid at the head section of the channel only. Further downstream the wave height is gradually reduced due to friction and energy dissipation at cross section changes. Moreover, the wave may disintegrate into a wave train.

For a periodic wave of period \( T \), the wave length is obtained from the expression \( L = cT = \sqrt{gD} T \). Taking \( T = 5 \) min \( = 300 \) s as a characteristic period of a calving wave (see the following section) and \( D = 500 \) m, a wave length of about 20 km is calculated.

**Surge waves**

Surge waves are generated by icebergs moving away from the glacier terminus after a calving, see figure 2.
Figure 2. Glacier - iceberg - fjord - system.

Denoting the accumulated width of the detached icebergs by $b$, their mean draught by $d$ and their velocity by $v_i$, we have

$$Q_{\text{max}} = bd_i v_i.$$  \hspace{1cm} (4)

The back flow between and beneath the icebergs has been neglected, which will actually tend to reduce $Q_{\text{max}}$. Combining equations (3) and (4), we obtain a wave height of

$$H = \frac{bd_i v_i}{(Bf^2D)}.$$ \hspace{1cm} (5)

For the purpose of illustration, consider the case described by Sorge (1933). For this case $b/B \approx 0.25$, $d \approx 550$ m, $D = 700$ m and $v = 2.5$ km per 10 min = 4 m/s. With these figures we get $H = 6.7$ m in excellent agreement with the wave height of 6-7 m observed by Sorge near the glacier front.

**Periodic waves**

Large icebergs detached from a glacier at a calving, very often turn over (Drygalski, 1897; Sorge,
1933) and consequently will reach the state of floating equilibrium only after a series of vertical oscillations - translatory as well as rotational (i.e. heave and pitch motions respectively).

However, icebergs that float away from the ice front after calving in an "upright" position which is typical at some calving glacier fronts in Greenland (see e.g. Carbonell and Bauer (1968)), will in general also perform heave and pitch motions, the reason being that the front region of a calving glacier will very seldom be in free floating equilibrium, either due to tides or because of bending deformations as described by Reeh (1968). Also the part of the glacier that remains attached to the ice sheet after calving will react to the changed force conditions at the front by an immediate elastic response, and consequently will start performing vertical oscillations while approaching a new state of equilibrium.

By the oscillatory motion of the ice mass, a flow - likewise oscillatory - is induced in the water beneath the ice mass, which works like a huge pair of bellows alternately drawing in the water of the fjord and expelling it. In the following a model will be set up for this vibration phenomenon.

In order to simplify the presentation we consider the situation where the width of the ice mass is large compared to the length of its floating part (the case of plane strain). Consequently a beam theory approach applies. The more general case of a plate theory approach has been treated by Reeh (1970).

Figure 3 illustrates the model of calculation. The differential equation for the vertical motion of the beam may be written

$$-\frac{\partial^2 M}{\partial x^2} + g \rho g u + \rho_i h \frac{\partial^2 u}{\partial t^2} = 0,$$

(6)

where $M =$ bending moment, $x =$ horizontal coordinate, $g \rho g =$ density of sea water, $g =$ gravitational acceleration, $u =$ deflection of the beam from the free
Figure 3. Model of calculation.

floating equilibrium position, \( p \) = pressure change caused by the flow of water beneath the beam, \( \rho_i \) = density of glacier ice, \( h \) = beam thickness, and \( t \) = time.

Applying the inviscid fluid approximation for the flow of water beneath the beam, the following equations apply

\[
d \frac{\partial v}{\partial x} - \frac{\partial u}{\partial t} = 0, \quad \rho_w \frac{\partial v}{\partial t} + \frac{\partial p}{\partial x} = 0, \tag{7}_{1,2}
\]

where \( d \) = depth of the water layer and \( v \) = flow velocity, assumed to be distributed uniformly with depth.

Introducing dimensionless quantities by

\[
\tilde{u} = \frac{u}{u_0}, \quad \tilde{x} = \frac{x}{l}, \quad \tilde{t} = \frac{t}{(l/\sqrt{gd})}, \quad \tilde{v} = \frac{v}{(u_0\sqrt{g/d})}
\]

\[
\tilde{\rho} = \frac{\rho}{(\rho g u_0)}, \quad \text{and} \quad \tilde{M} = \frac{M}{(\rho g u_0 l^2)},
\]

where \( u_0 \) and \( l \) are a characteristic deflection and a characteristic length of the ice mass, equations (6) and (7)\(_{1,2}\) may be rewritten

\[
- \frac{\partial \tilde{M}}{\partial \tilde{x}} + \tilde{u} + \tilde{\rho} + \frac{1}{8} \frac{\partial^2 \tilde{v}}{\partial \tilde{t}^2} = 0, \tag{8}
\]

\[
\frac{\partial \tilde{v}}{\partial \tilde{x}} - \frac{\partial \tilde{u}}{\partial \tilde{t}} = 0, \quad \frac{\partial^2 \tilde{v}}{\partial \tilde{t}^2} + \frac{\partial \tilde{\rho}}{\partial \tilde{x}} = 0, \tag{9}_{1,2}
\]

where \( \gamma = \frac{\rho_w l^2}{\rho_i nd} \) is a dimensionless parameter.
Assuming $\partial x/\partial x = 0$, equations (8) and (9)$_{1,2}$ may be combined to

$$\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial t^2} + \frac{1}{\gamma} \frac{\partial^4 u}{\partial x^4} = 0. \quad (10)$$

This is the basic differential equation for the vibration of a floating ice mass with consideration of the water flow beneath the ice. The further course to be taken depends on whether the ice mass can be regarded as a rigid body as is the case with an iceberg, or whether elastic deformations of the ice mass are essential, as they are in case of a floating glacier tongue attached to a grounded ice mass and possibly also supported along the sides by valley walls. We shall start by treating the iceberg-case and next summarize the results of the floating glacier case, previously presented by Reeh (1970).

**RIGID BEAM (THE ICEBERG)**

The oscillatory motion of a rigid beam is described by the equation

$$\ddot{u} = \ddot{U}(x) \sin \omega \tilde{t}, \quad (11)$$

where $\ddot{U}(x) = ax + b$, and $\omega = \text{frequency of oscillation}$.

Combining this equation with equations (9)$_{1,2}$ and (10) respectively, we get

$$\nabla \cdot (\dot{\gamma} a \dot{x}^2 + b \dot{x} + C_1) \omega \sin \omega \tilde{t}, \quad (12)$$

$$\ddot{p} = (\dot{\gamma} a \dot{x}^2 + b \dot{x}^2 + C_1 \dot{x}^2 + C_2) \omega^2 \sin \omega \tilde{t}, \quad (13)$$
\[ \ddot{\omega} = \frac{1}{(1 - \omega^2/\chi)} \left[ \frac{a x^3}{b} \ddot{x} + \frac{\ddot{\omega}}{\omega} ( \frac{\ddot{x}}{\chi} a x^2 \dot{x} + \frac{\ddot{x}}{\chi} C_1 x^2 + C_2 x^2 + C_3 x^2 + C_4 x^2 ) \right] \sin \omega \dot{\omega}, \quad (14) \]

\[ \ddot{\alpha} = \frac{1}{(1 - \omega^2/\chi)} \left[ \frac{a x^3}{b} \ddot{x} + \frac{\ddot{\omega}}{\omega} ( \frac{\ddot{x}}{\chi} a x^2 \dot{x} + \frac{\ddot{x}}{\chi} C_1 x^2 + C_2 x^2 ) \right] \sin \omega \dot{\omega}, \quad (15) \]

where \( \ddot{\omega} = \frac{\ddot{\omega}}{\omega} \) is the transverse force, and \( C_1, C_2, C_3 \) and \( C_4 \) are constants of integration to be determined by the boundary conditions.

At the free ends of the beam \( (x = \pm b) \), the transverse force and the bending moment vanish. Therefore, from equations \( (14) \) and \( (15) \) we obtain

\[ C_1 = \alpha \left( \frac{1}{\chi} - \frac{1}{\omega^2} \right), \quad (16) \]
\[ C_2 = \beta \left( \frac{1}{\chi} - \frac{1}{\omega^2} \right), \quad (17) \]
\[ C_3 = \alpha / 120, \quad C_4 = b / 384. \]

From the boundary conditions relating to the velocity and pressure of the flow, the constants \( C_1 \) and \( C_2 \) can now be determined in terms of \( a \) and \( b \) by means of equations \( (12) \) and \( (13) \). Next the frequency of oscillation \( \omega \) and the corresponding mode can be found from equations \( (16) \) and \( (17) \).

The assumption made so far that the width of the floating ice mass should be large compared to its length, will often be a rather poor approximation as far as icebergs are concerned. However, except in the case of heave motion of a circular iceberg situated at a great distance from confining walls restricting the flow (the axis-symmetrical case), relaxation of this assumption will substantially complicate the mathematics.

For the axis-symmetrical case, equation \( (9) \) should be replaced by the following equation

\[ \frac{\partial^2}{\partial \tau^2} + \frac{\partial^2}{\partial \tau - \frac{\partial \xi}{\partial \tau} = 0. \]

For heave motion, we have

\[ \ddot{\alpha} = b \sin \omega \dot{\omega}, \quad (18) \]
and consequently
\[ \ddot{v} = k \beta \dot{w} \sin \omega \tilde{t}, \]  
(19)

and
\[ \ddot{p} = \frac{1}{4} \beta \dot{w}^2 \left( \tilde{r}^2 - \frac{1}{4} \right) \cos \omega \tilde{t} \]  
(20)
since according to the boundary conditions, \( \ddot{v} = 0 \) for \( \tilde{r} = 0 \), and \( \ddot{p} = 0 \) for \( \tilde{r} = \frac{1}{4} \).

In dimensionless form, the equation of motion of the iceberg reads
\[ \frac{1}{8} \frac{\ddot{\tilde{u}}}{\tilde{r}^2} + 8 \int_0^1 (\tilde{u} + \tilde{p}) \tilde{r} d\tilde{r} = 0. \]

Substituting in this equation for \( \tilde{u} \) and \( \tilde{p} \) by means of equations (18) and (20) respectively, the frequency of oscillation \( \omega \) can be determined.

Figure 4 summarizes the iceberg vibration results for four different cases of practical significance. It appears that the dimensionless frequency of oscillation may for all cases be written
\[ \omega = \frac{k}{(1 + k/\gamma)}, \]
where each case is characterized by a specific value of \( k \).

In the limits of large or small \( \gamma \)-values, simplified expressions may be derived. For large/small \( \gamma \) we have \( \omega = \sqrt{k} \) and \( \omega = \sqrt{\gamma} \), respectively. The corresponding periods of oscillation become
\[ T = 2\pi \sqrt{\frac{\gamma}{k^2}} \]  
(21)\textsubscript{1,2}
\[ T = 2\pi \sqrt{\frac{\rho_i h}{\gamma g}}. \]

For a large Greenland iceberg, characteristic dimensions are \( 1/h \sim 1 \) and \( 1/d \sim 100 \). The corresponding value of \( \gamma = \frac{\rho_i l^2}{(\rho_i h d)} \) is of the order of magnitude 100, indicating that the limit of large \( \gamma \) is the more interesting from a practical point of view. From figure 4 it appears that the quantity \( 2\pi \sqrt{k} \) ranges between 0.8 and 4. Therefore, taking \( l = 500 \) m and \( d = 5 \) m as characteristic values for a large
Figure 4. Different cases of oscillatory motions of icebergs.

a) Infinitely wide iceberg distant from obstacles restricting the flow.

b) Infinitely wide iceberg near a vertical wall.

c) Infinitely wide iceberg confined between two walls.

d) Circular iceberg distant from obstacles restricting the flow.

1 denotes heave motion, 2 denotes pitch motion.

Greenland iceberg, the period of oscillation, as calculated from equation (21)₁, will be in the range 1 - 5 minutes.

It is interesting to compare the periods obtained for the two modes of an iceberg near a vertical wall T₁ = 4.0 l/√gd and T₂ = 1.1 l/√gd to the corresponding periods of the seiche in a bay of length l and depth d, which are T₁ = 4.0 l/√gd and T₂ = 1.3 l/√gd, respectively.

The rather small differences between the two sets of periods indicate, that the iceberg oscillation is mainly determined by the flow of water beneath the iceberg.

As regards equation (21)₂ which is valid in the limit of small y, this period is identical to the periods one would obtain for the heave and pitch
Figure 5. Dimensionless period of oscillation versus dimensionless parameter $¥$ for different cases of oscillatory motions of icebergs. Notation in accordance with the text in figure 4.

motions of a body floating in deep water if the "hydrodynamic" mass is neglected. However, for long calving waves, the limit of small $¥$ is not of much interest as stated previously.

In figure 5 the dimensionless periods for the different iceberg cases are shown as functions of $¥$.

The graphs illustrate the asymptotic behaviour for large and small $¥$ respectively, in accordance with the discussion above.

THE ELASTIC BEAM

The theory of an elastic plate covering shallow water was presented by Reeh (1970). Here a brief account of the more simple problem of an infinitely wide plate (plane strain) will be given. In this case the bending moment is related to the deflection
by the equation

\[ M = -\frac{Eh^3}{12(1-\nu^2)} \frac{\partial^2 u}{\partial x^2}, \]  

(22)

where \( E \) = Young's modulus, and \( \nu \) = Poisson ratio.

Figure 6. Dimensionless natural frequency of the fundamental vibration of the infinitely wide glacier as a function of the dimensionless parameters \( \beta \) and \( \gamma \).

Figure 7. Dimensionless natural frequency of the fundamental vibration of the glacier of finite width as a function of the width to length ratio \( B/l \) and the dimensionless parameter \( \beta \).
Assuming $\partial h/\partial x = 0$, combining equations (6) and (22), and introducing dimensionless quantities, the following differential equation emerges:

$$\frac{\partial^2 h}{\partial x^2} + \beta \left( \frac{\partial^2 h}{\partial y^2} - \gamma \frac{\partial^2 h}{\partial x^2} + \frac{1}{8} \frac{\partial^4 h}{\partial x^4} \right) = 0. \quad (23)$$

where $\beta = 12 \gamma \sigma in \frac{g L^2 (1 - \nu^2)}{(E_0 h)^3}$ is a dimensionless parameter.

Equation (23) together with relevant boundary conditions defines an eigen-value problem which can be solved by standard methods, see Reeh (1970) for details.

Figures 6 and 7 illustrate the results obtained for an infinitely wide glacier and for a glacier of finite width, simply supported along the side margins.

With reasonable choice of glacier dimensions and values for the elastic parameters of ice, periods of oscillation of several minutes may be derived by means of the curves in figures 6 and 7.

CONCLUSIONS

The occurrence of long calving waves in Greenland seems to be restricted to narrow fjords headed by major outlet glaciers from the ice sheet.

The waves are characterized by wave lengths of the order of magnitude of tens of kilometres and wave heights up to ten metres or more. Periods are typically in the range 1 to 10 minutes. The waves may constitute a risk to constructions near the shore lines of the fjords even at sites located several tens of kilometres from the glacier fronts.

A model of calculation in which the ice mass is treated as a heavy plate covering shallow water, predicts periods of oscillation of the same order of magnitude as those observed. The larger the ice mass and the more shallow the water beneath the ice, the longer is the period of oscillation. The period of oscillation is rather sensitive to the depth of water beneath the ice mass, which is seldom known
accurately. Soundings of water depth and iceberg draught are therefore required where accurate predictions of calving wave periods are required.

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REFERENCES


ICE SHEET DYNAMIC MODELLING WITH ENGINEERING APPLICATIONS: A NON-STEADY STATE ICE FLOW MODEL FOR THE MARGINAL ZONE OF THE GREENLAND ICE SHEET.

SUMMARY

The recent development in ice sheet dynamic modelling is briefly discussed. It is concluded that ice sheet dynamic modelling can now provide quantitative solutions to specific problems. Examples are given of previous applications of glacier dynamic models to solve engineering problems in glacierized regions. Very likely the need for such studies will increase in the years to come, due to the growing economic interest in the Arctic.

A model study of the response of a marginal sector of the Greenland ice sheet to mass-balance changes is described in more detail. The ice sheet sector is divided into individual sub-glaciers, reflecting the characteristic regions of the ice margin: glacier tongues with landbased termini, glaciers terminating in calf ice producing fronts, and interjacent ice margin sections. For a selection of these sub-glaciers, the response during the last 1000 years is calculated using an ablation history generated by means of a 2600 years long climatic record determined from data measured along an ice core retrieved at DYE 3 on the south Greenland ice sheet. The calculated response is in agreement with ice margin fluctuations, which are either observed or estimated by other methods.
The model is used to predict the ice-margin fluctuations for future decades. It is concluded that the present ice-margin recession will continue for at least some decades, unless a dramatic deterioration of the climate occurs in the near future leading to conditions similar to those in the coldest periods of the so-called "Little Ice Age".

Finally the complicated interrelationship between ice sheet dynamics and ice margin hydrology is discussed. It is concluded that changes of the ice thickness may cause changes in both the sub-glacial and supra-glacial drainage patterns.
ENERGY PLANNING IN GREENLAND

Abstract

To-day 98% of the energy supply of Greenland is covered by oil. This fact has caused serious consideration due to the isolated position of Greenland.

So in the autumn of 1981 an energy plan for Greenland was worked out. It was the aim of the energy plan to reduce the vulnerability of the present energy system by introducing various energy sources. According to the plan it would be possible in the year 2000 to cover 50% of the energy consumption of Greenland by hydro power, to cover 30% by coal - and to lower the demand for oil to 20-25%.

GTO has made investigations for hydro power since 1974. The investigation covers a number of small basins on which the community energy supply may be based in the coming years.

Such trends in energy supply will have an effect on urban planning. As a result it will be necessary to accept the construction of a substantial part of the housing accommodation as high-density urban areas.

Since 1974 GTO has also conducted an energy saving project at existing buildings and at the heating systems. The main purpose is to reduce the heat loss and utilize the fuel better, without changing the indoor comfort.
1 GENERAL CONDITIONS

Generally the energy supply in the Arctic region are due to undergo radical changes. The situation in Greenland is characteristic for this region.

To-day the energy supply in Greenland is 98% dependent on imported oil. In addition, a special quality of oil is in question, which is produced by a special refining process from North Sea oil, so that it can stay viscous at low temperatures. Though it does not at once look like difficulties of supply will arise in future years, political interventions may cause shortage of oil at short notice.

The isolated situation of Greenland, being a large island in the Arctic Ocean, makes the country particularly vulnerable. A re-adjustment of the energy supply, which will reduce the almost total dependence on oil, is of great present interest. Especially bearing in mind that such re-adjustment will take years.

In the light of this, Greenland Technical Organization (GTO) has prepared an energy plan for Greenland, a plan that will change the supply pattern entirely when being concluded in the year 2000. According to the plan the energy supply may be re-adjusted in a way that Greenland in the year 2000 only will have to use 20-25% oil in the energy supply. The rest of the supply will be covered by 50% hydro power and 30% coal. (Fig. 1).

![Fig. 1.](image)

According to the energy plan the supply may be re-adjusted in a way that Greenland in year 2000 only will have to use 20% oil in the energy supply.
2 OIL DEPOSITS IN GREENLAND

Till this day oil or gas deposits have not been found in Greenland. - In 1975 a number of major oil companies drilled for oil offshore West Greenland. However, all drillings turned out dry. Since then drillings for oil have not been performed.

However, new research activities are started this summer onshore on the East coast of Greenland, and of course there is a possibility of striking oil during this decade. Until an oil field, which can be used for commercial purposes, has been made ready for production yet another ten years may easily pass. Furthermore, the carriage of oil from Greenland is difficult, because it must take place by means of large ice-breaking tank vessels. In other words, it seems that oil production in Greenland may not be for a long time yet.

3 COAL DEPOSITS IN GREENLAND

Coal deposits are to be found in several places in Greenland. - Since the energy crises occurred in the midle of the 1970's more systematic investigations of the coal reserves in Greenland have been instituted and a major deposit was found in West Greenland. But calculations show that coal mining from the deposit cannot compete with coal imported from e.g. Scotland or Poland.

4 URANIUM IN GREENLAND

Uranium ore has been found in the southern part of Greenland. The quantity of uranium place the deposit among the medium deposits of uranium in the world. An actual mining of ore may at the earliest come up in the 1990's assuming that political support to the mining can be obtained, which is not probable.
5 HYDRO POWER IN GREENLAND

Greenland's alpine coast with the many deep fiords causes that only relatively few, major hydro power potentials exist. However, innumerable possibilities of establishing minor hydro electric power stations exist.

Not until in the middle of the 1970's did GTO start systematic investigations of the possibilities of building hydro electric power stations. We began by investigating the major occurrences which possibly could supply the very energy demanding industries with cheap energy e.g. in the production of ammonia, aluminium, and ferrosilicium. Calculations of profitability of such plants proved that it was not of current interest to perform intensive pre-investigations but sufficient to keep the areas under observation. (Fig. 2).

Fig. 2. Hydro potentials where systematic investigations are going on. The majority of the population is living on the south west cost.

- Marmorilik
- Nugssuaq
- Rade elv
- Pakitsuq
- Kugssup tasia
- Taserssuaq
- Taserssaq
- Isuakasia
- Gapiarfluup sermieq
- Buksefjord
- Isortuassup tasia
- Gradefjord
- Bjarnesund
- Iterdla
- Isorssua
- Grenseland
- Johan Dahl Land
- Taseq
- Motzfeldt se
- Redekammen
- Tusiussarsuk
- Anmagssalik
- potentials for communities: 800 - 1,700 GWh
- potentials for industries: 6,000 - 10,000 GWh
Instead the interest was directed towards the possibility of exploiting the many small deposits for regional consumption. During this investigations the GTO has found app. 40 minor reservoirs close to the towns, where hydro electric power stations may be built. In most cases minor potentials are in question with a possible energy production of 3 to 45 GWh/annum. Some of the potentials are somewhat larger with quantities of energy of 75 to 350 GWh/annum. In some towns it will be possible to cover the entire energy consumption as to electricity and heating by hydro power and at the same time obtain a certain surplus of cheap energy, which can be used in local industry. However, the most common is that minor hydro power stations will contribute to the energy supply of the town, however, without a complete coverage.

6 WIND POWER PLANTS AND SOLAR ENERGY IN GREENLAND

The GTO has mounted wind gauging stations at several places in Greenland in anticipation of obtaining the necessary facts for dimensioning of windmills, which are able to work under the conditions in Greenland. - In the planning period until 2000 it is realistic only to consider wind power a complementary energy source able to cover of few percentages of the requirements.

Observations show that the number of hours of sunshine, even in the northern part of Greenland, corresponds to Denmark. However, preliminary expenses of solar energy plants are still high and in the period of planning it is not anticipated to become of immediate importance to develop solar energy to any extent.

7 THE PRESENT ENERGY SUPPLY IN GREENLAND

The actual situation is, that every town in Greenland already has a power station, which capacity is sufficiently large to cover the requirements of the town. There is no possibility of joint opera-
tion between the power stations in the individual towns on account of the large distances. Therefore, so far it has been most profitable to base the production of electricity on diesel power in these relatively small local power stations.

The community in Greenland has since the 2nd World War changed from being a low energy society to a high energy society. The energy consumption has been multiplied by five in the period of 1960 to 1980. Per capita the energy consumption is 75% when you compare with the consumption in Denmark.

8 THE MAIN GOAL OF THE ENERGY PLAN

It has been an essential goal to the energy plan of Greenland to decrease growth of energy consumption without reducing the conveniences of the consumers. The energy planning guides toward the usual 3 main fields:

1. Saving of energy with the consumers.
2. An energy economical production of heating and electricity.
3. Use of other energy resources than oil.

The energy plan must be regarded as a superior plan which states the main directions. The actual energy planning appears for each town in close collaboration with the local authorities.

In the energy plan special considerations have not been taken to meet emergency situations. To-day, Greenland already holds a storage capacity corresponding to 12 to 15 months' of consumption which is to parry the initial effects of a critical situation.

8.1 Savings with the consumers

In the existing categories of dwellings, which naturally still for many years will consume the major part of the energy, considerable savings in oil consumption can be obtained by re-insulating the
houses and especially by adjusting the heating system and by a more energyminded operation. In general savings of averagely 25% can be obtained.

In the energy plan it is recommended that public financial support is granted to the carrying through of these energy saving measures. The energy plan suggests that a consultative arrangement is established which in every case may secure that the measures rest on a technically and financially sound basis.

Finally, the energy plan suggests that an energy conservation campaign is carried through in Greenland. The initiative for this must come from the Home Rule in Greenland. In so doing the effect of the campaign may become considerably higher than if done by the Danish Government.

8.2 Production savings

As mentioned previously, to-day all power stations are diesel-powered and up to the middle of the 1970's it has not been thought of using the residual heat on account of the low prices of oil. Units, which can exploit the residual heat in the exhaust gas, are now being mounted in our power stations, and the efficiency will raise from 35 to 65%.

8.3 Alteration of energy supply

The third main goal of the energy plan - utilization of other energy resources except oil - aims at making Greenland less dependent on a single energy resource and aims at obtaining the lowest possible costs of the energy supply on a long view.

An actual centralized energy supply for Greenland as a whole i.e. from a couple of major hydro electric power stations is not possible on account of the large distances between the towns. Separate energy plans to the individual towns should be prepared, in which
first and foremost it is tried to develop possibilities of establishing minor hydro electric power stations in the surroundings of the town.

By means of a preliminary going through of the possibilities, which are available town by town, we arrived at the conclusion that app. 50% of the energy supply in Greenland in the production of electricity and heating in the year 2000 could be covered by hydro electric power stations, and 30% by steam power stations based on imported coal.

In the majority of the power stations, as mentioned, residual heat plants have been established with district heating grids. Therefore, the electricity from a hydro electric power station is used most appropriately for producing heat by mounting electro-boilers in the power station and continue the exploitation of the district heating lines.

In towns, where there is no possibility of developing hydro power, it is possible with an economical satisfactory result to build steam power stations based on coal. However, good economy depends on the fact that the stations at the same time produce heat, meaning that a widely ramified district heating system should be constructed. The energy plan reckons with using foreign coal, but the possibility of using coal from Greenland is not excluded on a long view.

The alterations in question, both of hydro power and of coalburning plants will to a great extent lead to a collective heating supply. The alteration to such collective supply from a single energy station, which produces electricity as well as heat, is not that radical in Greenland. Large areas in the central parts of the town are already supplied with heating from district heating stations, meaning that they already have a district heating system to which the main lines from the energy station can be connected.
9 THE INFLUENCE OF THE ENERGY PLAN ON THE TOWN PLANNING

In the town planning up to now, the consideration that the expensive road systems, sewerages and water supply systems, should be exploited the best possible, has caused a number of bindings. In the future considerations to an economical energy supply will mean further bindings in the town planning.

As a consequence of the high costs at the construction of the district heating conduits, it will be necessary to accept the construction of a substantial part of the housing accommodation as high-density urban areas. And the multi-storey houses and small apartment-blocks should be situated in the vicinity of the energy station. In other words a development which is conflicting to the wish of the Greenlanders for single-family houses and an open view.

10 TOTAL INVESTMENTS AND RUNNING EXPENSES

The total investments for the accomplishment of the energy plan are estimated at 3.5 billions Danish kr. which correspond to app. 350 mio. of US Dollars. The running expenses will, after concluding the energy plan be diminished by 50%.

So far, the Danish Government has been responsible for the energy supply of Greenland. - However, future energy supply is a field which as regards finances running expenses as well as security of supply is of the utmost importance to everyday life of the population. Therefore the Greenlandic Home Rule now wants to take over the responsibility for the energyfield.
TOWN PLANNING AND HOUSING IN GREENLAND

Abstract

The development work in Greenland started in 1950. It concentrated on active combatting of diseases, extensive construction of houses and better education.

Greenland Technical Organization (GTO) was established as a government body, to handle all technical activities.

The development over the past 35 years has brought about a considerable amount of change in the Greenlandic society. The existence of the population is today mainly based on monetary economy. The nature of the towns has changed altogether.

The Home Rule has now taken over the responsibility for the country planning and the local councils are responsible for the urban planning.

Greenlanders prefer open cities and a good view. They want to live with, and not in defiance of, nature. It is important to respect these feelings when planning towns.

Building cost are high in Greenland. Thus, the Danish government offers subsidies overaching 85% of the building price.

The requests of the Greenlanders to the standard of the dwellings are the same as those of the people in the milder regions. They
want to take part of the material benefits, offered by the technolog- 
ological development. And the reason, why no special arctic residen-
type has been developed, is probably rooted in this fact.

THE POPULATION

Up to the Second World War, the Greenland people were a people in
misery - from a modern health point of view.

The development work really started to accelerate in 1950, when a
commission set out the guidelines for the development of a modern
Greenlandic society. This work was almost 100% financed by the
Danish Government. The basic idea of the development work was that
of extending the health service over a few years and concentrate
on active combating of diseases.

Extensive house building was to be implemented too, with a view to
contributing towards an improved state of health through an im-
provement in the housing situation.

Population Rate Growth 1950-1981

<table>
<thead>
<tr>
<th>Year</th>
<th>The entire population</th>
<th>Persons born in Greenland</th>
<th>Persons born in Denmark</th>
</tr>
</thead>
<tbody>
<tr>
<td>1950</td>
<td>23,642</td>
<td>22,581</td>
<td>1,061</td>
</tr>
<tr>
<td>1955</td>
<td>27,100</td>
<td>15,234</td>
<td>1,867</td>
</tr>
<tr>
<td>1960</td>
<td>33,140</td>
<td>30,378</td>
<td>2,762</td>
</tr>
<tr>
<td>1965</td>
<td>39,615</td>
<td>35,132</td>
<td>4,483</td>
</tr>
<tr>
<td>1970</td>
<td>46,532</td>
<td>38,912</td>
<td>7,620</td>
</tr>
<tr>
<td>1975</td>
<td>49,666</td>
<td>40,390</td>
<td>9,276</td>
</tr>
<tr>
<td>1981</td>
<td>50,643</td>
<td>41,459</td>
<td>9,184</td>
</tr>
</tbody>
</table>
The existence of the population which in the past was almost exclusively based on subsistence economy, is today mainly based on monetary economy. The majority has turned into wage earners in the wessels, the fish processing plants, the enterprises and the administration. - And this influences on the housing situation as well. (Foto: J. Svensson).

Over the years Danish labour has been replaced by local labour. Today 85% of the work in the technical sphere is being done by local artisans and labourers.
Education was given a high priority as well.

In 1950, the average life expectancy was but 34 years. In 1980, it had risen to 62 years.

The Greenlandic population has doubled over the past thirty years. But the Danish population has increased ninefold.

The heavy growth in the Danish minority reflects the need of assistance from outside during the building up period. Greenland did not have - and still has not - sufficient trained manpower to handle the many tasks involved in a modern society.

The Danes in Greenland still constitute a minority group. Only one fifth of the population are Danes. It is the official policy, that the Danes have to leave the country as soon as Greenlanders want to take over the responsibility for activities, the Danes have taken care of.

Live resources i.e. fish, birds and mammals still constitute the major occupational basis. But the existence of the population which in the past was almost exclusively based on subsistence economy, is today mainly based on monetary economy. The majority has turned into wage earners. - And this influences on the housing situation as well.

2 GREENLAND TECHNICAL ORGANIZATION (GTO)

It was anticipated that the development work would entail much building and construction work. Thus, Greenland Technical Organization (GTO) was established as a government body. GTO was to handle all technical activities so as to ensure the coordination of this work.
When GTO started working in 1950 in fact, little was known of which technical solutions would apply under Arctic conditions. Not much experience could be joined from abroad, either. - Technology had not yet made its entry into the Arctic area.

The technological development over the past 35 years has brought about a considerable amount of change in the Greenlandic society. The most obvious part of the development is the establishment of a large number of new buildings and technical facilities, raised and installed in the Greenland towns and settlements. The nature of the towns has changed altogether.

The detached small houses of the post have been replaced by urban buildings forming the framework around a complex society which technically is at the same level with similar societies in Denmark.

The buildings have assumed a specific Greenland character of their own. A Greenland building technique and architecture has been developed.

In all technical fields, solutions have been developed to operate under the specific conditions prevailing in Greenland. This applies not only to building work but also to the fields of power supply, roads, ports, air ports, water supply, sewerage etc. Today the technical environment in the Greenland towns is well developed.

During the initial development period, extensive use was made of Danish contractors. Over the years Danish labour has been replaced by local labour. Today 85% of the work in the technical sphere is being done by local artisans and labourers. A considerable number of local private companies have been established. They have taken over the work of Danish contractors. - But most of them are owned by Danes who have settled in Greenland.
Originally it was thought that the Greenlandic town ought to be compact and protects its inhabitants - with the magnificent scenery outside. This was a typical European way of thinking.

Greenlanders want to live with, and not in defiance of, nature. They prefer open cities and a good view. It is important to respect these feelings when planning towns.
3 TOWN PLANNING

Both in Greenland and other Arctic areas, we have had to experiment to construct the right type of town required. The philosophy of planning from the mild zone in Europe or U.S.A. cannot just be transmitted to the Arctic areas.

Originally it was thought that the Greenlandic town ought to be compact and protects its inhabitants - with the magnificent scenery outside. This was a typical European way of thinking.

Greenlanders prefer open cities and a good view, even if it should be a little windswept.

Observations in Alaska, The Northwest Territories, Greenland and Siberia suggest that the indigenous populations in Arctic areas want to live with, and not in defiance of, nature.

It is important to respect these feelings when planning towns. Even if it is easier and cheaper to provide high density town areas with public utilities, you must bear in mind that the local population prefer to live in scattered communities.

The Greenland population got home rule in 1979. The Home Rule had taken over the responsibility for the country planning in 1981. The Greenlandic politicians now establish the basic lines for the development of trade and industry, population localization, town and hamlet development etc. Thus, the central Greenlandic authorities have also gained decisive influence on the localization and design of house building.

The local councils are responsible for the urban planning.
4 HOUSING

Like other areas of the Arctic regions, up to the Second World War Greenland had no local house building tradition upon which a development could be based.

The bulk of the population lived in home-made huts, made of peat, rock, and drift wood. These huts undoubtedly represented the maximum attainable based on entirely local conditions established by nature herself. But their construction did in no way offer qualities justifying attempts to promote further development with a view to establishing proper houses for the local population. They could be described as nothing but highly dangerous.

A few houses had been constructed as modest imitations of the Danish civil servant residences. These wooden houses built by the local population itself were, however, usually of the same poor quality as the peat wall huts - poorly insulated and leaky as they were. But at least they did have an inherent potential for development into something acceptable.

Thus, house building in Greenland during the 1950s did actually use this type of building for the take-off: The idea was to let the Greenlanders go on building their own houses.

However, it soon became evident that one thing is to build kayaks and make fishing and hunting tackle to an age-old tradition, but building houses is something entirely different. A completely unknown technical know-how was required. In the middle of the 1950s it was realized that professional assistance was indispensable to the important task of providing houses for the population acceptable in terms of human relations and of health.

This task was entrusted to GTO who started off by standardizing the constructions of a few single-family house types.
Greenland technical Organization started the house building in the 1950's by standardizing the construction of a few single-family house types. The technical equipment of the houses was modest.

The house types formed a range varying greatly in size, but the materials and principles of construction were rather uniform. Local craftsmen and companies were able to construct these houses.
The house types formed a range varying greatly in size - and thus in price - but the materials and principles of construction were rather uniform. The technical equipment of the houses was modest. It was limited to coal-fired stoves and in towns having a power supply, electric light installations, too. However, there were neither water nor sewerage facilities. Local craftsmen and companies were able to construct these houses.

At the beginning of the 1960s, conditions influencing the housing situation changed considerably. The concentrated effort of the health service to combat especially the tuberculoses, ravaging Greenland as a national disease, now proved effective. The population figure increased by 34% during the 1950s. Also, people seemed more inclined to move from the settlements to the towns.

Thus, it became evident that the accelerating need of housing could not be covered solely by building comparatively small and primitively equipped single-family houses, scattered in the area. As long as the number of houses in the towns remained moderate, primitive water supply and simple house wastewater discharge could be accepted. However, houses were now to be provided for many more people and in a small number of towns, too.

Under these circumstances, town hygiene of a standard as low as the one people had got used to could not be accepted. Modern water supply and actual sewerage facilities had to be established. Such facilities were, however, costly in the rocky landscape of Greenland.

For maximum utility of the precious facilities - and also with a view to using the limited town areas suitable for building sites - building had to be undertaken in a more concentrated form than people had grown accustomed to. The building type selected was that of multistorey houses.
In the 1960's it became evident that the accelerating need of housing must be covered by building multistorey houses. This building type was selected for maximum utility of the precious water supply and sewerage facilities - and also with a view to using the limited town areas suitable for building sites.

Around 1970, there was a reaction against the multistorey type of housing. Thus housing schemes of recent years have been revised.
At the particular time, efforts were being made throughout the entire industrialized world - and thus in Denmark, too - to develop an actual building industry, and it seemed obvious to follow up this development in respect of the Greenland housing schemes. The great housing expansion was implemented by Danish contractors whereas local craftsmen also acted as sub-suppliers for the contractors. However, in the course of development, some of the local companies grew in size, toq, both in respect of capacity and know-how - and they have now taken over the construction of large house building schemes, too.

The reaction of the population to living in multi-storey houses - a type of housing people had only heard about - was, of course, anxiously awaited. However, it seems that people have got used to the idea rather quickly, probably not least due to the technical facilities not known in the primitive single-family houses: Central heating, warm and cold water, bathroom, waterflush closets etc.

Around 1970, there was a certain amount of reaction against the multistorey type of housing in Greenland similar to that encountered in Denmark - and in Europe.

People have reacted against the "confusing and boring" large housing areas, the term "grey concrete slum" has been used. Thus, housing schemes of recent years have been revised. Much lower multi-storey houses, row-houses, and single-family houses in groups have been built.

5 INTERIOR DESIGN AND STANDARD

The Greenlandic way of life has changed considerably with the increased standard of living and the change in the pattern of occupation.
Much lower multistorey houses, row-houses, and single-family houses in groups are now being built.
The original fishing and hunting trades have taken on a status of a more recreational kind of activity to many people, and as such make their mark on the interior design. This is duly expressed in the access facilities to the house or flat. In many new dwellings, the entrance is a combination of a front room and a sturdy and spacious scullery in which overcoats, boots and various gear, such as fishing tackle may be cleaned and kept, and where the catch may be cleaned and prepared. This scullery-entrance is the only special Greenlandic solution. The rest of the lay-out do not differ with regard to design and equipment from that of similar houses in recent European building developments, leaving aside the fact that room sizes are slightly smaller than in Denmark.

In 1980, in connection with a status for the housing situation in Greenland a comparison has been made of the housing standard at Nuuk/Godthaab, capital of Greenland, with the housing standard at Copenhagen, capital of Denmark. Standard criteria were the percentages for residences with and without central heating, bathroom and water closet in the two capitals.

Certainly the majority of the residences at Nuuk/Godthaab have been built after 1960 whereas in Copenhagen there is still a large number of residences dating back to the time before 1900. Thus, it is natural that the comparison shows an average housing standard somewhat higher at Nuuk/Godthaab than at Copenhagen.

<table>
<thead>
<tr>
<th>Capital</th>
<th>Nuuk/Godthaab</th>
<th>Copenhagen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residences with central heating</td>
<td>88%</td>
<td>67.4%</td>
</tr>
<tr>
<td>Residences with a bathroom</td>
<td>79%</td>
<td>63.4%</td>
</tr>
<tr>
<td>Residences with a water closet</td>
<td>74%</td>
<td>93.8%</td>
</tr>
</tbody>
</table>

6 PUBLIC UTILITIES

The towns have got the steady and adequate power supply which is a must if a modern urban community is to work properly. All houses have electric installations.
The Greenlandic way of life has changed considerably with the increased standard of living and the change in the pattern of occupation. But the building cost are high. Thus, the Danish government offers subsidies averaging 85% of the building price.

The towns have got the steady and adequate power supply which is a must if a modern urban community is to work properly.
The towns have got a reliable whole year water supply of a satisfactory quality from a hygiene point of view. The considerable cost of blasting or excavating underground lines means that only some of the consumers - primarily those using the largest quantities of water such as hospitals, industrial plants, and high density housing areas - receive water from the water lines.

Along with a reliable water supply, sewerage is a condition of appropriate urban hygiene. In Greenland, uncleaned waste water is led straight into the open sea. The health authorities have deemed this justifiable as long as the current conditions are good, and the waste water volume is negligible in comparison to the water renewal in the outlet area.

In areas, with scattered houses, for instance in single-family housing areas, it is usually not financially feasible to provide sewerage. Thus, there is still a need of a compulsory night soil removal arrangement allowing for proper and hygienic conditions of removal.

The refuse collection and disposal in the towns is organized and all households have to join this arrangement.

A road network providing reasonable access to all buildings is a condition, that night soil and refuse removal, fire-fighting services, delivery of goods, among other things, may be implemented. Roads in Greenland towns are to absorb internal traffic only. There are no roads between the individual towns.

It is important to the tidiness in the towns that the areas between buildings are re-established after the building workers have completed their work. The ground care according to which the areas are regulated, sown or consolidated is a condition, that the towns may be kept clean.
The towns have got a reliable whole year water supply of a satisfactory quality. Along with water supply, sewerage is a condition of appropriate urban hygiene.

A road network providing reasonable access to all buildings is constructed in the towns. There are no roads between the individual towns. Roads in Greenland towns are to absorb internal traffic only.
Building costs are high in Greenland. Thus, the Danish government offers subsidies averaging 85% of the building price. Only by way of such heavy subsidizing, houses - which are appropriately healthy - may be provided for a population whose primary basis of living is constituted by the live resources.

Attempt have frequently been made to simplify the technology transferred, but it may not be made primitive. The requests of the people in the cold regions are in this respect obviously the same as those of the people in the milder regions. They want to take part of the material benefits, offered by the technological development. And the reason, why no special arctic residence type has been developed, is probably rooted in this fact. - People in the Arctic want to live in the same way as people do at a more gentle climate.

It is a common characteristic that people in the cold regions - not least the younger part of the population - prefer blocks of flats to the simple single-family houses. Everywhere, this is due to the conveniences of cold and hot water, a bath, a toilet, central heating etc. - in fact the possibilities of benefiting from improved conditions of hygiene and health.

People would, of course, preferably live in a single-family house area with the full technical equipment but for reasons of economy this is not possible for the majority of the inhabitants in these part of the world where the construction of water lines, sewers, and roads is very expensive.

*  

The Home Rule and the local councils have announced that they want to take over the full responsibility for the housing sector in 1987. At the same time, the Danish government will offer them annual subsidies corresponding to the current government expenses to housing and to utilities delivery.
Examples of Harbours and Harbour Constructions in the Greenland Towns and Settlements.

At the conference in Narsarsuaq the Greenland Technical Organization gave an account explaining how the extension of major harbour facilities have been accomplished over the past 30 to 40 years.

Harbour construction in Greenland is generally characterized by the great depths of water close to shore which rule out the possibility of extending harbours in traditional manner by means of an outer harbour and an inner harbour. Most harbours are built on locations offering natural shelter, considering at the same time the possibilities of establishing the necessary hinterland.

The choice of materials, protection of wood by impregnation, corrosion-proofing of steel, cathodic protection of steel structures or preparation therefor, requirements of concrete and added materials, etc., do not in Greenland give occasion for problems different from those applying to harbour constructions in other places and under other conditions.

What primarily decides the structural design of a harbour facility is the topographical and geological aspects of the area, i.e. the floor conditions, the location and inclination of the rock formation, the nature and extent of the deposits, the possibility of anchoring, etc.

We will now review some examples of projects having different structural designs.
There will be three contributions:

1. Mr. Hulgaard, technical director for consulting firm Hostrup-Schultz and Sorensen at the conference in Narsarsuaq made a contribution dealing with constructions on steep mountain sides. This included an account of the Strong Point Project at Nuuk for the ocean tanker (round steel boxes on a blasted shelf anchored in the mountain wall). At this seminar Mr. Hulgaard will explain the implementation of this construction and in particular give details of the choice of materials.

2. Mr. C. P. Olsen, technical director for consulting firm Dansk Geoteknik will give an account of various and typical structural designs subject to different conditions, and will do this based on the projects the firm has been dealing with through the years.

3. Ilulissat Harbour.

We heard yesterday the lecture "long period calving waves" by N. Reeh.

Model experiments for Ilulissat harbour carried out in 1958 proved that by building a 53 m long southern jetty and an approx. 40 m long northern jetty coupled with the establishment of an undersea floor wall in the entrance it would be possible to dampen seiching by approx. 50% at the Atlantic quay and by approx. 65% in the inner harbour. The jetties have been built, but the undersea floor wall still remains to be established.

The problems of calm conditions in the inner harbour were accentuated at the time by the plans to extend the industrial facilities, as the expected larger fleet of cutters were to berth in the inner harbour (the boat harbour).

Mr. Hans P. Steenfos, director for consulting firm Bigum & Steenfos will explain in this connection the problems associated with determining the berthing conditions in the inner harbour, including location of a berthing quay in deference to the seiching effect in the inner harbour and the trouble caused by the presence of ice and eddying.

Mr. Steenfos will present alternative suggestions for designing the berthing quay and review the paper on the final location.
BERTH FOR 30 000 T TANKER - NUUK (GODTHAB), GREENLAND

INTRODUCTION

In my paper for the Narssarssuaq seminar I have focused upon some quay structures in Greenland with respect to the influence of ice on the design. One of the projects exemplified in the paper is the 30 000 t tanker berth in Nuuk.

In this paper I shall cover in more detail how the structures for the tanker berth were built and shall explain how the design took into consideration the special conditions in Nuuk to make the structures as convenient as possible for the contractor to fabricate and erect.

If we examine existing quays structures in Greenland from the contractor's point of view we will find some typical conditions.

1. The quays are usually very short to reduce the cost irrespective of the water depth being great or moderate. This means that heavy equipment very often is too costly to mobilize and use advantageously.

2. The work has to be planned with due allowance for the winter season with darkness, ice formation, and low temperatures.

3. The tidal range is rather large in Greenland and the maximum range is reached in Nuuk, where it is about 5 m.
The mean tidal range at spring time is about 4.4 m.

The large tidal range is considered to be an advantage for the contractor if his work and the design is well planned.

Only very seldom the tide will give currents of any importance for the harbours due to the great water depths usually found in Greenland and the fact that most harbours are placed in bottom of a bay.

4. The occurrence of 'storis' (field ice) in the area is very difficult to predict.

For the actual site in Nuuk, field ice occurs on average only every fourth year according to the Greenland Pilot. Nevertheless, the field ice has reached Nuuk more often during the last 15 to 20 years, typically in July or August.

DESIGN

The berth is designed for a 200 m long tanker with max. 30 000 t oil and the necessary water depth at mean water level is 15 m. As an absolute minimum, two strong points are necessary to steady the ship. The usual platform for hose handling was omitted to reduce cost and construction time. Instead the hoses are carried on the ship's deck and pulled ashore via the southern strong point.

In front, the strong points are equipped with rubber fenders. These fenders are placed at a rather low position because of the low freeboard of the fully loaded tanker and of the low water level.
Each strong point consists of a steel caisson with 6.4 m diameter, and about 22 m height. It is filled with sand and at the top of the caisson, at +5 m, it is braced by steel beams to the rock face. The caissons are founded on a horizontal ledge blasted into the rock slope at level -18 and standing on an 0.5 m thick layer of concrete. The circular cross section of the caissons was chosen with the object that earth and water pressures inside the caissons are transformed to pure tension making it possible to fabricate the walls of steel plates.

The thickness of the steel plates is basically 10 mm, but at certain levels the plates are thicker.

20 mm thick plates are used at the bottom – where the earth pressure is maximum – and at the support for the rubber fenders. Also, between levels where the maximum corrosion occurs in Nuuk (-2 to -3 m) the plate thickness is 20 mm.

The caissons are further designed for a differential water level corresponding to the internal water level being at the top of the caisson even at low water. This situation was considered to be unavoidable during the sand filling process.

The design of the berth was made in cooperation with GTO and the shore installations were designed by the Danish consulting engineers Nielsen & Rauschenberger A/S.

THE EXECUTION

The fabrication and erection were executed by the Danish contractor E. Pihl & Son A.S. during the two summer seasons in 1975 and 1976.
During the first year the underwater work was made and the caissons were welded on a site situated 1.2 km from the site.

The caissons were welded from prebent plates while laying on the side on a series of sleepers. In that way it was easy to roll the caissons to have the best position during welding and painting.

In the next summer season, the caissons were easily rolled into the water after they had been fitted with a temporary cap to allow them to flow.

The weight of one caisson at this stage was about 60 t only which made it easy to handle and, moreover, the maximum draft was 1 m only.

The caisson was towed to a place where the water depth was 15 m and, by letting water inside, it was tilted to an upright position and then brought to the permanent place.

To resist the forces from possible waves (maximum wave height = 1.5 m) it was quickly filled with sand to level 0. This was followed by pouring of the concrete behind the rubber fenders and by the erection of the steel beams inside the caisson.

Next the bracing beams between the caisson and the rock face were placed. At the rock face they were fixed to in situ concrete bases already made. The other end of the beams was simply embedded in the thickened edge of the concrete deck slab so as to provide ample tolerance for the installation of the members.

Finally, the fenders were mounted on prepared steel brackets, and bollards, ladder, etc. were installed.
STEEL TRUSS AND ACCESS BRIDGE

CAISSON

SAND FILL

BEDROCK

D=6.4 m

0 5 10 20 m
Main Dimensions

Built: 1975-76
Contractor: Pihl & Son A/S, Copenhagen
Price in 1976: 5 mill. DKK = approx. 500,000 US$
Weight of steel per caisson: 60 t
Weight with sand fill: 850 t
Thickness of steel plates: Generally 10 mm

but
- at bottom due to high earth pressure
20 mm
- behind rubber fenders
- at level -2 m to -3 m
due to max. corrosion in this zone

Water depth: Minimum 15 m at mean water level = 12 m
at max. spring low water
Typical Conditions for Harbour Building in Greenland

1. Small Jobs
   Heavy equipment too costly to mobilize.

2. Winter Season
   Darkness, ice formation, low temperatures.

3. Tide
   Nuuk (Godthåb). At spring mean value 4.4 m.
   Julianehåb and Jakobshavn ~ 50% of Godthåb value.

4. Ice
   Field ice, winter ice, ice foot.
   Generally the harbours are well sheltered and ice forces are usually small.

5. Waves
   Great wind velocities may occur, but only within very limited directions. In Godthåb all storms are from S-SE. Long periodic waves may occur.

6. Current
   Current from tide is usually low due to location in bottom of bay. Wind generated current is unknown due to great water depths.

7. Soil Conditions
   Excavation extremely costly.
   Driving of piles and sheet pile walls difficult.
   Settlement problems are rare.
   Sand fill and rock fill available.
Conclusion

Conditions are different from Denmark, but in general not worse for the sites where existing harbours are placed.

However, planning is very important.
EXAMPLES OF HARBOURS AND HARBOUR CONSTRUCTIONS IN THE GREENLAND TOWNS AND SETTLEMENTS

Introduction.

This POAC session in Jacobshavn deals with examples of Harbours and Harbour Construction, which have been carried out during the 25 year development plan, which started around 1960. The technical aspects have been ruled by GTO, and as consultant, Dansk Geoteknik A/S has been one of the firms, who assisted in the building of harbours, quays, slipways, shipyard transfer systems and shipyard cranes along the western coast of Greenland.

I will in the following give a review from this period, describing special and typical examples of construction, which have been chosen with regard to the maritime, meteorological, geographical and geotechnical conditions on the different localities.
Fig. 1.
Holsteinsborg, Hydrographic chart.

Geographical and maritime conditions:

Waves. Holsteinsborg harbour is situated at the end of a fiord with a natural harbour area sheltered by many islands and reefs with low water depth. In selective direction W, depths are 40 m to 70 m, giving 2 m waves at the harbour area at low occurrence intervals.

Tide and current. The tidal range is 4.4 m, HHWL is +2.8 m and LLWL is -2.8 m, when meteorological high- and low pressures also are taken into account. Tidal current is of no importance in the harbour basins, lying in the inner part of the fiord.

Ice situation is favourable for the inner harbour, without ice floes coming from south. Normally the harbour is open in the winter-time, without any fast-ice.
YEAR 1  BULKHEAD, ANCHORED STEEL SHEET PILING WITH SANDFILL
YEAR 2  WOODEN SUPERSTRUCTURE OF SPACED PILES AND STONEFILL.

YEAR 1
BULKHEAD, ANCHORED STEEL SHEET PILING WITH SANDFILL
YEAR 2  WOODEN SUPERSTRUCTURE OF SPACED PILES AND STONEFILL.
Holsteinsborg Atlantic Quay, anchored bulkhead of steel sheetpiling with wooden superstructure.

Geological conditions are difficult for construction, because of thin layers of loose sand covering a bedrock at 40° inclination.

Geotechnical conditions are good except for the thin layers of sand, giving problems with scaffolding and sufficient depth for driving of sheet piles.

Sandpumping can be used to improve geotechnical conditions, and this method was introduced in Holsteinsborg for the first time in Greenland in 1964.

Construction chosen. The construction is normally an anchored bulkhead of steel sheet piling with sandfill, and a wooden superstructure. Due to the risk that a wall in full height should be exposed to waves, and due to the great extent of the complete work, the construction had to be carried out in 2 summer seasons.

In the first year the sheetpile bulkhead was completed being left for the wintertime with a stone protection on the sandfill at level -0.50 m.

In the second year the wooden superstructure was built and filled in with crushed stone obtained from the rock excavation in the harbour areas.

Temporary state and scaffolding. Due to the thin layers of soil covering the bedrock, cushions of sandfill were pumped directly into the bottom with spreaders on the valves, to disperse the kinetic energy and to settle the sand.

Normal scaffolding for the walls could then be supported by vertical piles and batter piles. Sufficient passive pressure for the wall could thus be obtained for the wall in the temporary state.

Sheetpiling, waling with double channel profiles, and anchoring. These works have been of normal and typical standards and need no further comments.

Main anchor block. This was intended to be rock anchored, but due to poor rock concrete anchor blocks were introduced.
Berm of quarry stone. The ready state of a sheet pile wall needed increased passive pressures, which could not be obtained from a sandfill. A layer of crushed stone was therefore placed on the bottom in a width of 15 m, thereby obtaining the sufficient earth pressures in the passive zone. The berm of stones is at the same time a safeguard against erosion, caused by turbulence of ship screws.

Wooden superstructure. This was all made from tropical hardwoods, which are resistant to rot and marine borers.

Spaced piles being erected in outward bends of the sheetpiling, were made of basralocus.

Pile caps, upper wale and fendering were made of azobé.

Upper anchors. These anchors fasten the upper wale to secondary anchor blocks, which were cast in situ between the main anchors.

Sorted rockfill. Due to the open space between the piles, large sorted stones were filled in against the piles, and packed to avoid leakage of materials.

Crushed stone fill. The superstructure had to be sufficiently drained for excessive inside water pressures, which otherwise would be a danger, not only to the wall, but also to the total stability of the structure.
YEAR 1: CELLS OF STEEL SHEETPILING
YEAR 2: WOODEN SUPERSTRUCTURE OF SPACED PILING AND PLANKING WITH STONEFILL.
Holsteinsborg Quay for Supply and Outfit, cross section.

**Sheetpile cells.** The structure is sandfilled and consists of closed rectangular sheet pile cells with wooden superstructure. Dividing the structure into a superstructure built upon a basic structure, gives less temporary risk and also a possibility of choosing different materials in the 2 sections.

**Wooden superstructure.** Application of wood; eliminates all questions on corrosion of steel in the tidal range, where alternating exposure to salt water and air is being disastrous to steel.

Azobé, a tropical hardwood is completely resistant to deterioration by rot and marine borers, and together with stonefill, this should be an imperishable combination.

**Temporary state and scaffolding.** The distance between the front wall and the coastline is varying from 25 m - 60 m, and only a thin layer of soil covers the bedrock. Therefore it is difficult and risky, if not impossible, to make a girder scaffolding for a steel sheet piling in full height of 7 m. This should resist very big waveforces in the temporary state.

Waveforces have been reduced equalling a 4 m high wall by using sheet pile cells. Sufficient sandfill has been available for ramming of cells, which are stable by weight, when they are filled. When building cells from the shoreline and filling with sand, the next cell can be rammed from the previous, and so forth the cells form their own scaffolding.

**Waling and internal anchors:**

Closed azobé frames are prefabricated in azobé with spaced timber planks for mounting of bolts without boring. In the corners steel plates are used for assembling the timber planks, which are interlaced. The frames are mounted with 4 anchors and are used as support for the steel sheet piles during the ramming procedure.
**Lower anchoring.** The sheet pile cells need no inside anchoring as the active earth pressures on the lower front wall are transferred to outside walings. The latter are at the ends bolted to the transverse wall, which in turn transfers the forces to the back wall.

The lower outside waling cannot be built until dredging has been done. The outside waling must be built before the superstructure gives overburden load in the cells.

**Passive earth pressures.** At the footing of the wall passive pressures are necessary with a water depth of -5 m. Bottom protection with crushed stone is placed to guard against turbulence from ships screws.

**Rectangular cells.** In rectangular cells, anchor forces can be transmitted in the corrugated sheet pile walls by using sand on the sides to stabilize the profile.

Special provision has been made for the welded junction sheetpiles, as forces are transmitted orthogonal to the wall. Special steel and controlled weldings are used for this purpose.

**Superstructure:**

**Spaced piling.** When the sheetpile cells have been filled in and anchored as a bulkhead, the superstructure is erected with azobé piles in every outward bend of the sheet piling.

**Azobé planking** is mounted, and tightness for quarry rock is secured by spaced planking, which also allows for drainage of inside water pressures.

**Drain filters.** To make an effective drainage of the sandfill in the superstructure, stone filters are supplied to level -2.20 m in outward bends of the sheetpiling. In addition rock fill and filter layers in the superstructure provide safe draining of the construction.

**Upper walings** of azobé timber are mounted and anchored to the backwall in the cells.

**Pile cap and fenders** are standard made from azobé, being very hard and resistant to wear from berthing of ships.
Fig. 4.
**Fiskeneset, Hydrographic chart.**

**Geographical and maritime conditions:**

**Waves.** Fiskeneset is situated in the northern part of the island Qeqertarsuatsiaq, and the trawler quay is partly sheltered towards all wind directions. The maximum wave height of 1 m seldom occurs and only at extreme conditions.

**Tide and current.** Normal tidal range is 4.0 m, HHW is +2.8 m and LLW is -2.8 m.

The current can be rather heavy, the maximum speed being estimated to approx. 1.0 m/sek., estimated.

**Ice situation.** Due to the current, solid-ice seldom occurs, and the ice thickness is limited. During winter the water is filled with sludge. In the summertime polar ice and glacier-ice occur in periods extensively with ice-cakes and floes being a threat to the structures.
BULKHEAD OF STEEL SHEETPILING IN FULL HEIGHT, 3 ANCHORS TO COMMON ANCHORBLOCK

UPPER ANCHOR AND WALING IN AZOBÉ

CAP AZOBÉ

MWL +2.00

MAIN ANCHOR

Mwl 0.00

ARTICULATION AND DIVIDED WALING

LWL -2.00

STEEL SHEETPILING LARSEN 22

PEBBLES

TIE RODS, NO WALING

-6.50

-70m

-60m

QUARRY RUN

COMMON CONCRETE ANCHOR BLOCK

ROCK ANCHORS

SHELF, LOCAL BLAST

STEEP BEDROCK

SHELF, LOCAL BLAST

CONCRETE SUPPORT CASTING AND ROCKANCHORS

FISKENÆSSET TRAWLER QUAY

FIG. 5
Figur 5. 
**Fiskemasset Trawlerquay, Bulkhead of steel sheet piling in full height, cross section.**

*Geological* conditions are extremely difficult, due to steep bedrock inclining 60° and continuing to a waterdepth of 60 m.

*Geotechnical* conditions are excellent with regard to sound bedrock without fissures and deterioration. Overburden to the bedrock is not existing as there is no soil covering giving problems to erection methods. The cantilever principle has to be used for the scaffolding.

*Construction principle chosen* consists of a steel sheet piling in full height from bottom -7.0 m to top +3.30 m.

*Anchoring* has been provided at 3 levels +2.10 m, -1.30 m and -4.50 m to a common concrete anchor block, which transfers all load to bedrock by use of injected rock anchors. To safeguard against inhomogeneities in the bedrock, the number of anchors are doubled.

*Shelf and concrete footing* for the sheet piling have been excavated by local blasting. The concrete support block and rock anchors have been introduced as additional safeguards, being unnecessary for the anchoring of the lateral forces, but an extra measure against blows from drifting ice floes.

*Walings* are prefabricated, the upper being a timber of azobé, and the lower being two spaced azobé timbers for easy bolting under water. They are integrated members of the scaffolding in order to support the sheet piling against wave forces during the erection period.

*Scaffolding* is not shown, but all wave forces of alternating thrust and pull are transmitted by anchors and timbers from the walings to the common concrete anchor block, being the first construction detail to be fulfilled for temporary support.

*Lower anchoring at level -4.50 m* has no underwater waling, but are tierods from every inward bend of sheet piles. Holes in the sheetpiles are prefabricated and furnished with wedge formed washers before the piles are mounted.

*Common anchorblock* has been furnished in 3 different modes, with steel profiles, cams and tubular holes, for easy mounting of upper, intermediate and lower anchors respectively.
Pebbles is the first material to be filled in the bulkhead, doing no harm to the tierods by being dumped.

Quarry Run is the second material to be filled in carefully between all anchors by crane. Around all anchors crushed stone is packed to prevent damage from occasional dumping of big stones.

Drainage of the bulkhead fill is very efficient following the tide due to the application of crushed stone having a great void ratio. In the outward bends in the sheet piling, special vertical drains are inserted having a sufficient flow capacity to avoid inside water pressures to build up.

Stability. When filling in a structure with 3 anchors intersecting at the same point of a common anchorblock, special demands arise to the scaffolding, and to avoid any vertical displacement of the wall relative to the fill. This is ensured by bolting the walings, and by anchoring the toe of the walls into the concrete casting.
SECTION OF BULKHEAD ANCHORING

QUAY FRONT

8.5m

WESTERN WING

STEEL SHEET PILING, LARSEN 22

CONCRETE CANTILEVER WALL

ROCK ANCHORS

UPPER ANCHOR
INTERMEDIATE ANCHOR
LOWER ANCHOR
COMMON ANCHOR BLOCK RL CONCRETE

FISKENÆSSET
TRAWLERQUAY

FIG. 6

DANSK SEOTEKNIK A/S
GRÆNSKADEHUS 9
3060 BLOSTUP
DENMARK
Fig. 6.
Fiskensasset Trawlerquay, Section of the bulkhead anchoring.

The plan shows one half of the bulkhead.

**Wings** are built as concrete cantilever walls from shore and to level -1.0 m. The walls are fixed to rock with injected rock anchors.

**Bulkhead front** is anchored at 3 levels by inclined anchors to a common concrete anchor block, which has been cast on a shelf blasted at MWL 0.00 m.

**Common anchor block** is of prime importance for erection of the scaffolding, and it is the first structural member to be built.

3 different anchoring details are provided on the top of the anchor block.

1) **Double channel profiles** are placed vertically, projecting above surface, and cast into the anchor block.

   Upper anchors provided with eyes are bolted to the channels. A tightening socket is included.

2) **Cams** in concrete and projecting above the surface of the anchor block have an inclined back side, which is furnished with tubes for inserting of intermediate anchors. These can be directly tightened at the back side.

3) **Niche and tubes** placed with the selected inclination provide for the inserting of the lower tie rods. These can in turn be tightened directly from the back side.

**Articulations** in the upper and intermediate anchors have been provided at the walings, thus eliminating the demands for tolerance. The articulations are formed by V shaped hooks in the walings, coupled with schackles to the eyes welded on to the end of the anchors. In this manner spherical articulation is obtained.

The flexibility of the long slender anchors will facilitate the remaining needed adjustments between walings and anchor blocks.
Geographical and maritime conditions:

**Waves.** Sukkerktoppen is situated on the island of Manitsoq. The harbour is totally sheltered towards W, N and E, but opens towards SE and towards the fiord between some islands. At seldom occasions 1 m waves can occur in the outer basin, where fish industry, atlantic quay and slipway are situated.

**Tide and current.** Tidal range is 4.2 m. MHWL is +2.1 m and MLWL is -2.1 m, without meteorological high and low pressures taken into account.

Current is of no importance in the harbour basins, as they form the inner part of a fiord.

**Ice situation** is favourable for the inner harbour in the summer time. Ice floes can occur, but without endangering the structures. The harbour is normally open in the wintertime.
Fig. 8.  
*Sukkertoppen, Layout of Fish Industry and Cold Store.*

The site plan shows the NE corner of the Atlantic Quay, and the contour of 10 m water depth. The position of the Trawler Quay is the last possibility for building further deepwater quays in Sukkertoppen, and the Trawler Quay with Cold Stores shall, according to development plans be in close contact with the Atlantic Quay. The quays will also be used by the same road and bridge connections to the town.

Frontline of the Trawler Quay shall intersect the northern corner of Atlantic Quay following the direction of the -10 m contour towards NE.

Berthing of a 60 m LOA trawler will not interfere with the berthing of atlantic ships.

Geotechnical conditions are unfortunately worst possible, as will be seen from the next illustrations.
The two profiles are positioned with origo in the NE corner of the Atlantic Quay. It is noted that a 20 m deep cave in the bedrock between st. 25 and st. 75 is filled with postglacial sands at level -15 m. In turn both profiles show a top layer of organic silt varying from 2 m to 5 m in thickness. The contour of the quay front is shown at the eastern side, being the utmost position to get full use of the 10 m depths in the basin.
Fig. 10.
Sukkertoppen, Geological cross sections in st. 43, st. 56, st. 72 and st. 81.

The cross sections show the planned front, and it is clear, that the upper two cross sections, being the western end, are worse for building purposes than the lower two cross sections, being the eastern end.

The eastern end has nearly bare bedrock inwards, but the rock surface falls very steeply in st. 72 m. However, sands are found at level -14 m, and if the covering organic silt is dredged away sufficiently and substituted with sandy material, stability of the structures can be obtained.

The method is known as "geotechnical fortification", and has been the only identified economical solution, especially as piling is impossible due to the steep bedrock sloping 80°.
SHEET PILE CELLS WITH WOODEN SUPERSTRUCTURE, CROSS SECTION.
PRINCIPLE: GEOTECHNICAL FORTIFICATION.

PILE CAP AZOBE
SPACED PILING AZOBE
FENDERING AZOBE
PLANKING, GEOTEXTILE, TIGHTENING
FRONT WALL LARSEN 32
TIE RODS, MUTUAL BETWEEN WALLS
OUTSIDE WADING BETWEEN TRANSVERSE WALLS, AZOBE
BOTTOM PROTECTION CRUSHED STONE
STEEL SHEET PILING

UPPER WALE
UPPER ANCHOR

TRANSVERSE WALL LARSEN 32
WALING, FRAME OF AZOBE WITH ANCHORS, PREFABRICATED
BACK WALL LARSEN 32
ANCHORS
-4.00

ANCHOR SLAB

BEDROCK
TEMPORARY SANDFILL CUSHION

SANDFILL

H WL -2.1
L WL -2.1
M WL 0.0

0 5 10 m

DANSK GEOTEKNIK A/S
GRÅSKOVEN 6
2600 GLØRUP

SUKKERTOPPEN TRAWLER QUAY FIG 11
The structures are sandfilled and consist of closed rectangular sheet pile cells, which are anchored into concrete anchor slabs, thus ensuring the total stability on the steep rock surface.

On top a structure of spaced azobé piles is built with azobé planking, tightened with geotextiles and filled with sand.

Dividing the structure into a superstructure built on a base structure gives less temporary risk and a possibility of choosing different materials.

The wooden superstructure eliminates all questions concerning corrosion of steel in the tidal range with alternating exposure to salt water and air, being disastrous to steel.

Azobé, a tropical hardwood is complete resistant to deterioration by rot and marine borers, and is regarded as imperishable.

**Temporary state and scaffolding.** The distance between the front wall and the coastline is concerning 30 m, and the bedrock has no overburden. It is therefore difficult and risky to make a girder scaffolding for a steel sheet piling at 9 m depth. Furthermore, the structure should resist very big waveforces in the temporary state.

Waveforces have been reduced equal to 4 m depth by substituting the organic silt with sand, combined with a temporary sandfill cushion to level -4.0 m. In this way sufficient sandfill has been made for rammed cells, which are stable by weight. When building cells from the shoreline and filling with sand, the next cell can be rammed from the latter, and so forth. The cells themselves form the scaffolding extending 30 m from shoreline to the quay front.

**Anchorings.** Closed cells demand long running meters of sheetpiles for the walls. Several anchor levels are needed to reduce the bending moments, i.e. weight of steel. The cells have 4 anchorlevels.

1. **Upper anchoring and walings.** Each cell has been furnished with pre-fabricated closed frames of azobé. Mutual anchors are used for support of sheetpiles during ramming, as each new one is supported on the previously completed one.
2. Intermediate anchoring at level -4.0 m. Between front- and backwall tie rods are mounted on all single inward bends of the walls. In this way no waling is necessary. The level is -4.0 m, which is on top of the temporary sandfill cushion.

3. Lower anchoring. The sheet pile cells need no inside anchoring as the active earth-pressures on the lower front wall are transferred to outside walings. These are at the ends bolted to the transverse wall, which in turn transfer the forces to the back wall.

The lower outside walings cannot be constructed until the temporary sandfill cushion has been dredged away and filled into the cells. This must be done before the superstructure gives overburden load on the cells.

4. Passive earth pressures. At the footing of the wall, passive pressures are necessary with a waterdepth of -9 m. Bottom protection of crushed stone is laid to guard against erosion from turbulence formed by ships screws.

**Superstructure of tropical hardwood.**

**Spaced piling.** When the sheetpile cells have been filled and anchored as a bulkhead at level -0.5 m, the superstructure is erected with azobé piles in every outward bend of the sheet piling.

**Azobé planking** is mounted, and sandfill erosion is secured by geotextiles, which however allows for drainage of inside water pressures.

**Drain filters.** To make an effective drainage of the sandfill in the superstructure, stone filters are supplied to level -2.20 m in outward bends of the sheet piling.

**Upper walings** of azobé timber are mounted and anchored to the backwall of the cells.

**Pile cap and fenders** are standard made from azobé, being very hard and resistant to wear.
PLAN OF SHEET PILE CELLS

LARSEN 32 SHEET PILES

WESTERN WING

ANCHOR SLABS

ANCHORS

WALING OF CLOSED ABOE FRAMES, WITH ANCHORS, PREFABRICATED

EASTERN WING

NORTHERN FRONT

ANCHOR SLABS

SUKKERTOPPEN FIG 12
TRAWLER QUAY
Fig. 12.
Sukkertoppen Trawlerquay, Plan of sheetpile cells.

**Western wing.** From the shoreline and to the front 5 cells are built at a water depth of -5 m giving possibility for smaller boats to berth along 24 m length of quay.

**Eastern wing** has no depth of water, and is provided with a stone embankment, except at the outer corner cell being a cell of double length.

**Front of bulkhead** has 9 m water depth at a length of 14 m, being sufficient for the berthing of trawlers.

**Stability of cells.** The cells in the western wing are built from shoreline and filled with sand successively.

The double length cell in the center and the cells in the eastern wing are provided with anchors and anchor slabs to secure the stability in the ready state. Being rammed into a sandfill cushion, the anchoring must be completed before the cushion is dredged away and before the lower outside walings are constructed.

**Walings and internal anchors.**

**Closed azobé frames** are prefabricated in azobé with spaced timber for mounting of bolts without boring. In the corners steel plates are used for assembling the timber, which are interlaced. The frames are mounted with 4 anchors and are used as support for the steel sheet piles during the ramming procedure.

**Rectangular cells.** Using rectangular cells anchor forces can be transferred in the corrugated sheet pile wall, provided that there is sand on the sides to stabilize the profile.

Special provision has been made for the welded jointed piles, as forces are transmitted orthogonally to the wall. Special steel and controlled weldings are used for this purpose.
SHEETPILE CELLS WITH WOODEN SUPERSTRUCTURE, EASTERN WING

FENDERING, AZOBÉ

-3.00 PILE CAP, AZOBÉ

SPACED PILING, AZOBÉ

SPACED PLANKING AND
GEOTEXTILE TIGHTENING

WALINGS

EMBANKMENT

QUARRY, RUN

TEMPORARY
SANDFILL CUSHION

BEDROCK

POSTGLACIAL SAND

MUTUAL TIE RODS
BETWEEN WALLS

STEEL SHEET PILING

OUTSIDE WALEING
BETWEEN TRANSVERSE
WALLS, AZOBÉ

-9.0 BOTTOM PROTECTION

TIGHTENING TIMBER

TIGHTENING, BAGS WITH PEBBLES

0 5 10 m

SUUKERTOPPEN TRAWLERQUAY FIG.13
Fig. 13.
Sukkertoppen Trawlerquay, Eastern wing.

**Embankment.** Towards land the reclaimed area is embanked by quarry material being built upon the temporary sandfill cushion. Transport of sand is prevented by the use of geotextiles.

**Superstructure.** Use of imperishable tropical hardwood is described earlier.

**Tightening of sheet piles against bedrock sloping 1:2.** The western wing and front is straightforward as there is sufficient soil available for ramming.

The eastern corner cell is standing on steep bedrock, and although it is attempted to cut the sheet piles at angles before ramming, openings will be found at any single sheet piling.

**Tightening timber** has been bolted onto the bedrock before the temporary sandfill cushion was made, and bags filled with pebbles have been placed in the voids.

After ramming, careful excavation along the wall has been carried out from the top of the sand slope and downwards. During this process bags with pebbles have been placed successively between the wall and the timber.

**Outside walings.** Before filling in the superstructure, the sandfill is excavated along the front, and prefabricated *azobé* walings are mounted onto the wall, being provided with holes and welded nuts before ramming. Work by divers is thus limited to a minimum.
Geographical and maritime conditions:

**Waves.** Egedesminde is situated on a small island at the southern part of the Disko Bay. The harbour is totally sheltered to S and W, and partly sheltered to N and E. The design wave height is 1.6 m.

**Tide and current.** The normal tidal range is 2.6 m, HHW is +1.5 m and LLW is -1.6 m. The current is not significant.

**Ice situation.** In most winters Egedesminde has fast-ice conditions from medio December to primo May, thickness approx. 60 cm. The icebergs from Jacobshavn Ice-fjord are stopped by a row of small islands north of Egedesminde.
A new fish processing plant has been planned at Tipitooq situated 2.5 km from the town center of Egedesminde.

Geotechnical investigations and depth soundings have been carried out and the results show that a 25 m trawlerquay of 8 m depth and a 60 m quay of 5 m depth for fishing vessels, can be built according to the planned layout.

The inside quay for fishing vessels is traditional, but the new trawlerquay is lying on bedrock sloping 1:2 to 5 m water depth, with little or no overburden.
BULKHEAD OF SPACED PILING AND PLANKING, CROSS SECTION

- PRECASTED SPACED PILING, AZOBÉ
- SPACED PLANKING, AZOBÉ
- MWA +1.00
- MWL 0.00
- LWL -1.00

- UPPER WALKING AZOBÉ
- SPACED PLACING BASIS PILEUS
- LOWER WALKING AZOBÉ
- LOWER ANCHORS
- TEMPORARY BULKHEAD SUPPORTING PROVISIONAL SCAFFOLDING
- SECONDARY ANCHORS
- SECONDARY ANCHOR BLOCK
- QUARRY RUN
- ARTICULATION
- BEDROCK
- MAIN ANCHOR BLOCK
- ROCK ANCHOR

EGEDESMINDE, TRAWLERQUAY, FIG 16
Fig. 16.
Egedesminde Trawlerquay, Bulkhead of spaced piling and planking.

**Bedrock surface** is sloping 1:2, and it will be impossible to build up stone material to a natural slope. Dumping sand cushions will not be possible either.

**Quarry** material will be used as fill, due to the surplus material obtained from the blasting needed, to provide sufficient areas for the industry.

**Bulkhead construction** will have to be carried out using the cantilever principle.

A **temporary bulkhead** with its top at MWL and foot in -4,0 m is erected by scaffolding erected on bare rock with horizontal support on a main anchorblock. This is placed in reinforced concrete at MWL cast at dry conditions, and it is furnished with rock anchors for the ready state -8 m bulkhead. Temporary waling and piles are for no use in the ready state, and accordingly they are made of unimpregnated pine.

**Main anchorblock and scaffolding.** Scaffolding is done by use of cantilivered temporary horizontal piles, to be bolted onto the concrete block and supported at the end by temporary vertical piles. These are provided with steel footings anchored into the bedrock.

**Upper and lower anchors.** These are given the same dimensions as for the 8 m bulkhead, and they are fixed to the preliminary walings of the -4 m bulkhead.

**Articulations.** The anchors will be provided with articulations in such a way that they in a later stage can be extended to anchor the -8 m bulkhead.

**Walings of -8 m bulkhead.** Upper waling are of azobé in square timber, whereas the lower waling is prefabricated. It consists of a normal wale, bolted with "spacers" and a fastener timber, enabling the piles to be mounted without underwater bolting.

The walings are suspended from the scaffolding, which is cantilevered from the temporary bulkhead in accordance with the same principles mentioned above.
Construction chosen consists of spaced piles of basralocus combined with spaced planking of azobé. The latter allows crushed stone to be used without any criteria for screening of the material.

Below MLWL the spaced planking is prefabricated as girders to be mounted easily by divers above and below the lower waling. Above MLWL the planking is fixed directly to the piling.

Upper waling is of azobé being prefabricated with borings for anchors and tie bolts.

Upper and lower anchors. These are both provided with eyes for shackles at the inside end. The outward end is passing the wales and is furnished with adequate steel mountings for tightening of the anchors. The anchors are dimensioned to transfer all load to the main anchor block.

Secondary anchors and waling at top. These anchors are supplementary and especially designed for wheel- and crane loads on pavement near quay front. The anchors are inclined and fastened to the in situ cast secondary anchor blocks between the main anchors at MWL.

Fendering and pile caps. These are normal standards made from azobé.

Fill of Quarry run. This material is the only fill in the structure, and it shall be placed carefully by grab, neither damaging planking nor anchors. The crushed stone shall be packed at the anchors.

Protection against corrosion. All anchors and bolts are to be hot galvanised, and anchors in rock fill will be furnished with polyethylen turbular coating.
Fig. 17.

Slipways for 250 t dockweight and repair stands for 60 t dockweight.

Slipways have been built to the shipyards in the towns of Egedesminde, Holsteinsborg, Sukkertoppen, Frederikshåb, Arsuk and Julianehåb. As an example is shown a photo from Julianehåb. All slipways have been built as dams of quarry rock, having shoulders of big stones as protection of fast-ice, which moves up and down with tide.

Ice removal is difficult, and must be done by front end loaders (gummiged). This job has been disastrous in many places, and concrete slabs are now being used as pavement to protect rails, timber and bolts.

Fig. 17
In Julianehåb, Godthåb and in Jacobshavn, floating pontoons for handling of fish have been designed.

As an example is shown photos from Østre Vig in Godthåb. The pontoon is anchored by 2 steel girders provided with spherical articulations at each end, at the pontoon and at the abutment.

Between the parallel girders crossing chains have been suspended along the diagonals.

The gangway and the conveyer belt for transporting of fish, are both fastened to the quay side with spherical bearings. Bearings are shown on the pontoon allowing for free sliding on the pontoon surface. Displacements are limited by guiding rails on the pontoon.
In Julianehåb, Frederikshåb, Holsteinsborg and Jacobshavn facilities have been provided for easy docking and transfer of ships on a horizontal plane, mainly on rails.

As an example is shown the arrangement in Jacobshavn. The 63 t crane has here been constructed and delivered by Carl B. Hoffmann in Esbjerg.

The ship is berthed in a steel cradle, which is lifted onto the quay by a derrick crane. On the quay several rail tracks are radiating, and the ship is swivelled into the right direction, while still hanging in the crane, before placed on the right track.
EXAMPLES OF HARBOURS AND HARBOUR CONSTRUCTIONS IN THE GREENLAND TOWNS AND SETTLEMENTS

Mr. Steenfos delivered a lecture with slides on model tests concerning seiching and lay-out for the harbour of Ilulissat/Jakobshavn.
Erik Sprunk-Jansen, managing director
GREENEX A/S
DK-3963 Maarmorilik
Greenland

CO-OPERATION BETWEEN MINING COMPANIES AND THE LOCAL SETTLEMENT - THE MAARMORILIK CASE

Mr. E. Sprunk-Jansen delivered a lecture with slides on the above subject.
THE ENVIRONMENT AND THE MINING – THE GREENEX CASE

Introduction

Greenex A/S is a Danish limited company which since 1973 has operated a lead and zinc mine at Maarmorilik on the west coast of Greenland, 500 km north of the Polar Circle.

The name of the site, Maarmorilik, refers to the fact that large amounts of the mountain consists of marble, in Danish "marmor". A quarry was operated for some years to produce building stone which can be seen on several prominent buildings in Copenhagen. However, this exploitation was terminated before 1973.

Quite near to the marble quarry on the opposite side of the small fjord called Affarlikassa, a mountain rises rather steeply. It had long been known for a remarkable dark figure on its side resembling a flying angel. One might suppose that this was an exposure of an internal ore vein, however, this is not the case although – as we know now – the mountain in fact contained a large amount of extractable rich lead and zinc ore.

This is the basis for Greenex's activities.
The principle of the production in a highly simplified form is shown in figure 1. The ore is excavated in the mine at a height of about 700 m. By a cable conveyor it is brought from one side of the A-fjord to the other where a concentrator plant is situated.

In 1984, 675,000 tons of ore were ground and concentrated by consecutive flotation processes. 26,000 tons of lead concentrate and 122,000 tons of zinc concentrate were recovered and shipped to Greenex's customers for metal production.

Through the years the content of the ore has been around 4.5% lead and 13.5% zinc. Most of these metals have passed into concentrates and have thus been utilised, but unfortunately it is practically impossible to reclaim it quantitatively. Small amounts of lead and zinc remain in the waste - the so-called tailings.

In 1984, the activities gave rise to the production of more than 500,000 tons of tailings to be disposed of. The same method was used as in former years - namely deposition at the bottom of the A-fjord at a depth between 35-70 m.

A short description of the landscape is appropriate for understanding why this way of disposing of the tailings was chosen. As is seen from fig. 2, Maarmorilik is situated at the connection between the two fjords, Affarlikassa and Qaamarujuk. They are long narrow fjords.
with very steep mountainous banks. The only reasonably level area to be found is occupied by the Maarmorilik production plant and its connected buildings. It is therefore impossible to point out any suitable location where the enormous amounts of tailings can be placed.

Right from the beginning of the mining activity, it was therefore decided to deposit the tailings on the bottom of the A-fjord as already mentioned. At the time there was no fear of a polluting effect. Lead and zinc occur in the ore as sulphides, galena and sphalerite respectively. It is well known to all chemists that these compounds belong to the most insoluble ones. The deposition scheme could be considered quite harmless.

Nevertheless - should small amounts of metal be released, they were to be expected mainly to be held back in the A-fjord which, at its connection with the Q-fjord, has a threshold impeding the exchange of water between the fjords (fig. 3). At least in the western end of the Q-fjord the effect of the mining activity should be indiscernible. This was the claim mentioned in the concession from the Greenland authorities.

**Pollution is Observed**

It goes without saying that an extensive analytical control of the fjord water condition was established from the beginning. And much against expectations it was revealed that obviously the metal content in the tailings was not quite as insoluble as supposed.
Samples of fjord water for analysis were taken at several stations in both fjords, f.ex. at station 4 (fig. 3) which may represent the conditions of the A-fjord. As an illustration some of the results of the lead analyses are shown in fig. 4. Two things are seen - namely that the lead concentration varies systematically with the season, and that it shows an unfortunate tendency to rise over the years.

The Ministry for Greenland got concerned and demanded that Greenex did something to improve the situation materially, and it is just to say that Greenex went into the task fullheartedly.

It is felt that environmental protection is a natural matter of concern to the management of a modern industrial enterprise. Through the years Greenex has devoted considerable efforts in this field. The task has been a difficult one, being to a great extent a pioneer work. Although several other mines extract lead and zinc, their experiences have not been directly usable at Maarmorilik, where salt water - very inconveniently - has to be used in the concentrator.

Many studies have been made to understand the mechanism by which metals are dissipated in the environment, and many measures have been taken to improve the situation. Some have been futile, but many have been useful. Some of the more important topics are (fig. 5):
Hydrodynamics of the Fjord System

A schematic representation of the deposition of tailings is shown in fig. 6. The stream of tailings from the concentrator runs down to the bottom of the A-fjord where the tailings settle as a sediment. However, on the way down through the water, small amounts of metal are dissolved and small amounts of fine particles are suspended. The concentration of these materials is highest near the bottom, where they may stay for long periods because the bottom water is normally nearly stagnant. However, several impacts from the environment cause some movements of the water by which polluting metals are brought forward to the Q-fjord.

For instance, in the summertime a small torrent from a lake in the mountain falls into the inner part of the A-fjord and forms a superficial stream of fresh water through the fjord.
This is also shown in fig. 7 (the arrow marked Qf). The other important influence is from the wind, but both the fresh water stream and the wind circulation act in the surface layers. The transportation of metal to the Q-fjord is therefore moderate in the summer.

In winter the fjord is covered by ice, which excludes the influence of the wind.

However, another movement of the fjord water is caused by the ice formation. As is well known, when ice is formed in salt water only pure water is solidified and the salt remains in the water just beneath the ice cover. The density thus increases and the water sinks (Q3). A vertical circulation arises and lead containing water is brought from the deep to the upper layers from where it can rather easily proceed to the Q-fjord.

A similar mixing of the Q-fjord occurs from time to time when water from the Q-fjord with a high salt concentration intrudes into the A-fjord and presses the bottom water upwards (q2).

The Dam Project

Once it was conceived that the transportation of metal containing water to the Q-fjord could be effectively impeded by means of a dam built across the mouth of the A-fjord (fig. 8). This would mean, however, that the
quay, where the ore concentrates are loaded, had to be moved. Therefore, another idea arose. The tailings could be directed to the innermost part of the fjord and the dam could be built where the fjord is narrowest.

It was found that these solutions for one thing were very costly and that the construction would take rather long time. A more important consideration was that it would not be feasible to build an impermeable dam because large amounts of water would unavoidably be carried to the basin from the concentrator plant by the fresh water stream and form the precipitation over the mountains. It was judged that a dam would not be very efficient, and it has not been build.

The Metal Content of the Tailings

Instead great attention was paid to the properties of the tailings. The metal occurring in the fjord water must come from the metal content in the tailings and therefore it is endeavoured to lower this content. This is done by improving the efficiency of the concentrator plant. A large amount of modifications have been introduced. An auxiliary flotation plant for extraction of lead from the grinding circuit and considerable increases of the volumes of lead as well as zinc flotation plants are among the more important ones. The result is seen from fig. 9 showing that the lead content in the tailings has decreased from about 0.45% in 1975 to about 0.15% today. A similar change of the zinc content has been attained.
The Soluble Substances

It has been found that there is not a rigid relation between the metal content of the tailings and its tendency to release metal to the water. It was thought in the beginning that the release was caused by oxidation of the insoluble sulphides, but later it was found that the release of metals predominantly originates in the presence of small amounts of soluble metal compounds. These had not been discovered in the beginning as they constitute only about 1% of the total amount of metal.

An analytical method for determination of these small amounts was provided. From a scientific point of view it is not very exact, but has been a powerful tool in the battle against pollution. It has made it possible to determine the amount of soluble lead and zinc at every stage of the production process from the mine and through the concentrator until the tailings end in the fjord.

It appeared that certain amounts of soluble metal compounds are already present in the ore. In the case of lead only a minor increase due to oxidation may be observed. On the other hand the amount of soluble zinc is increased rather much on the passage through the concentrator. It was found that this was caused especially by zinc sulphate and copper sulphate which
were added as flotation reagents, and a sizable reduction in the use of these chemicals has brought about a significant improvement.

Chemical Treatment of the Tailings

However, after all the efforts to ameliorate the operation of the concentrator, it must be recognised that it is not possible to avoid small amounts of soluble metals in the tailings. It was therefore a great step of progress when it was found that the solubility could be reduced when the tailings were treated with certain chemicals. After a great number of laboratory experiments, aluminium sulphate and calcium hydroxide were selected. As the analytical control shows, aluminium sulphate has a strong depressing effect on the zinc solubility while lead is primarily influenced by the calcium hydroxide. A further addition of a flocculating agent makes the tailings precipitate quickly when it is dispersed in water thereby diminishing the time available for solution.

These new observations were introduced in large scale in 1979.

Fig. 10 shows the analyses before and after the introduction of chemical treatment of the tailings. The content of soluble lead drops from 41 to 14.5 ppm and for zinc from 290 to 88 ppm.
Effect in the Fjord Water

The corresponding improvement of the fjord water quality can be followed by analyses of the water in the deeper part of the A-fjord where the tailings from the concentrator are being discharged. Fig. 11 illustrates the variation of the concentration of lead and zinc in the bottom water from 1978 to 1980. In spite of the violent seasonal fluctuations the decreasing tendency of both concentrations is clearly discernible.

At least two influences act together. The earlier mentioned introduction of a flotation plant in the milling circuit and the later extension of the flotation volume - marked a and b in the figure - and the start of the chemical tailings treatment - marked c. The amelioration of the water quality is quite impressive. The troublesome increase of the concentration in the fjord water in the years up to 1978 - which was shown in fig. 4 - was stopped and it was now possible to proceed with the operation of the mine. It is true though that the concentrations of heavy metals are still high compared to the situation prevailing in the area before the mine was established. Therefore, Greenex continuously feels a strong obligation to search for further means of amelioration.
The Tailings Discharge System

Fortunately the total content of soluble compounds in the tailings is not dissolved. The dissolution requires some time and only a limited time is available while the particles sink through the fjord water until they end on the bottom and are covered by new particles shortly after. It is endeavoured in several ways to shorten this period of time. As already mentioned a flocculant is used which makes the particles sink rapidly. A special outlet arrangement for the tailings is constructed with the purpose that no air is entrained with the tailings stream, a fact that is important because air bubbles would tend to increase the dissipation of the particles. Also, care is taken that the lower end of the outlet tube is constantly situated only a small distance over the bottom.

It is also thought useful to take care that the water content of the tailings stream has as high a density as possible, preferably higher than the density of the bottom water. In this way a possible buoyancy effect would be hindered. One possible way would be to make use of high density salt water in the concentrator which could be produced as a by-product from the production of sweet water for domestic consumption. This possibility is being considered.
Atmospheric Pollution

The tailings are undoubtedly the main source of polluting material but there are other sources of some importance. It has for instance been shown that certain amounts of dust are spread through the atmosphere. Fig. 12 shows some analytical results from a lichen species, Cetraria Nivalis, collected from various places in the neighbourhood of Maarmorilik. It is clearly seen that there is a close relation between the distance from Maarmorilik and the lead content in the plants, indicating that the lead originates from the mining activities. Since this study was made, a number of dust sources of various sizes have been identified and remedied. One of the more important sources could be traced back to the mine. Dust is formed partly by the excavation of the ore and partly by the crushing of the ore. It is removed by the ventilation system which carries large quantities of air. This system has recently been supplied with a more efficient dust remover, a textile filter, and an important decrease of the airborne pollution is expected in the near future. As some of the dust must have fallen on the fjords, a decrease of the water pollution can also be hoped for.
The Waste Dump

The next source of pollution which should be mentioned are the so-called dumps. By the excavations in the mine it is often necessary to remove rather important amounts of ordinary rock, for instance to establish transportation ways. This waste material composed mainly of carbonates of calcium and magnesium has been deposited outside the mine on the slope of the mountain. One of the larger is the "old" dump on the north side of the Black Angel mountain, see fig. 13.

As is easily understood it is not always easy under the conditions prevailing in the mine to make a precise distinction between pure rock and rock with a limited ore content. It must be admitted that a certain amount of ore can be found in the dump.

Seaweed and Mussels

From time to time metal is released from this ore deposit and rain and melting water from the snow bring it down to the shore where it gives rise to an increased concentration in the surface water. This is where certain species of seeweed grow. The increased concentration is clearly reflected in an entranced metal content in the seeweed, which may be seen from fig. 14.
Seaweed was collected at numerous sites along the A-fjord and Q-fjord. At the various sites a vertical line depicts the lead concentration found in the seaweed. Around the A-fjord rather high concentrations are seen, but by far the highest concentration refers to the site just beneath the old dump.

In contrast to the tailings as a pollution source, the effects from the waste dump will not cease when the mining operation is stopped. For this reason Greenex looks at this matter with great seriousness. Today the only known way to counteract the unwanted effects is to remove the waste dump, an extensive job as it accounts to about 400,000 tons.

The effect of the old waste dump may also be seen in fig. 15 where some results of analysis of Blue Mussels are given. The Blue Mussel is an organism which is extremely sensitive to the presence of even small amounts of lead. It is possible to disclose the influence of the mining activities as far as 30 kilometers away. As with seaweed the lead analyses in mussels show higher values around the A-fjord, and a maximum value is found beneath the old dump.
Blue Mussels are the only animal organism in which the lead content attains so high values that it may be dangerous to eat in large amounts. It has therefore been recommended not to collect mussels for food within a certain area around Maarmorilik.

Results Accomplished

A number of possible sources of pollution have now been discussed and numerous remedies which have been introduced have been mentioned but nevertheless it has only been possible to touch on some of the more important topics. The discussion has been centered around lead, and zinc has only been superficially mentioned. Cadmium has been totally omitted. As this gives an incomplete picture of the range of heavy metals appearing it has also been necessary to curtail the description of the many experiments performed and the many alterations and improvements of the equipment and the processes in use. A lot of work is continuously being done to keep the whole operation under control. Having mentioned some of the methods of control, it is interesting to see some of the results achieved.

The condition of the water in the fjords can be described by calculation of the total amount in tons of lead dissolved in the great water volumes. In fig. 16 the upper curve shows the combined weights of lead in both fjords and the lower curve solely the weight of lead in the A-fjord so that the amount in the Q-fiord is represented by the distance between the two curves.
The curves show that the situation in a period around 1976-77 was characterised by a rather high content of lead in both fjords. Since then a remarkable and rather satisfying decrease has been accomplished.

More important is, however, that the impact on the fauna of the Q-fjord has been very limited. In order to follow and control the influence of the mining activities on animals and plants both authorities and Greenex have collected a great number of biological samples every year since 1972. The samples are being analysed for the heavy metals lead, zinc and cadmium.

The collected material comprises i.a. seals and the fish species: wolffish, halibut, uvak and ammassat, together with shrimps, mussels and seaweed.

The investigations have shown that in seals the mining activities have never caused any increased content of heavy metals, neither in blubber nor in meat, liver or kidney. Considering that seals constitute an important source of food this fact is very satisfying.

The investigations have also shown that there is no increase of the heavy metal content in fish meat. However, a modest increase of lead content has been demonstrated in whole ammassats and in wolffish liver. Apparently wolffish liver is an extremely sensitive indicator organism. The lead content in wolffish is shown in fig. 17 for the period 1978 to 1984. It appears that the lead content has been increasing until 1979.
Since then it has been decreasing simultaneously with the decrease of the lead concentration in the fjord water. This is one of the few examples of an effect of the improved water quality on biological material. In other instances the improvement has not been clearly reflected, probably because many organisms are unable to change their content of heavy metals rapidly.

**Impact on the Population**

An over-all consideration is that with the exception of the elevated lead content in mussels in a localised area around Maarmorilik, the mining operation has not harmed the human food resources like seal and fish in the area. Based on the analyses on hand and the statistical information on the food consumption of the Greenland population, it has been calculated that the intake of lead would run around 1/10 of the tolerable intake according to WHO of all fish and seal caught in the Maarmorilik area.

**Conditions after Closedown**

Sooner or later the operation of the mine will come to an end. It is difficult to say for how long the ore resources will last, perhaps 4 or 5 years. After closedown Greenex will endeavour to reclaim the site and the surrounding area.
Among other things - the waste dump has already been mentioned - attention is paid to the tailings lying as sediment on the fjord bottom. It is believed that after the tailings have settled it will release only small quantities of metal. A certain part of the small content of soluble substances have been released already while the particles were sinking through the water. Additional small quantities of soluble substances may be released from the bottom and further small amounts of the sulphides may be rendered soluble by oxidation. But in time a large reduction of the dissolution rate may be expected, partly because the available soluble substances are washed away and partly because the bottom of the fjord is covered by natural sediments. The small torrent earlier mentioned which falls into the inner part of the A-fjord carries about 2,500 tons per year of a particulate natural material, which in the main will settle in the A-fjord.

Some introductory experiments seem to show that the future release of metals from the sediments will be quite small. However, a more extensive series of experiments using seal sediment samples collected in the A-fjord are being planned. If, against expectations, they show an unacceptable rate of metal release, Greenex intends to cover the tailings sediment with a layer of ground natural rock and with sediments collected from a nearby site. Also this procedure has been studied by laboratory experiments, but additional experiments are included in the new experimental plan.
Greenex is confident that it will be possible to restore conditions close to the situation before start-up and that there will be no risk that the fauna and flora in the surroundings will suffer any damage. The goal is that the mine will be remembered only for its positive achievements and that nobody will tend to feel any anxiety about environmental problems.
**List of Illustrations**

1. Schematic picture of the production system.
2. Photo of the fjords.
3. Drawing of the fjords.
4. Lead concentration in the water at station 4 in the A-fjord. 
5. List of content.
7. Water movements in the A-fjord, summer and winter. 
   From DHI: Hydrografiske undersøgelser, April 1979, fig. 8.2.
8. The dams. 
9. Lead in tailings. 
   From årsrapport, miljøprojekter 1984, April 1985.
10. Soluble metals in tailings. 
11. Metals in bottom water from the A-fjord. 
   Ibidem.
12. Concentration of lead in Cetraria Nivalis. 
13. Photo of the old dump.
   From GGU and GFM: Recipientundersøgelse ved Maarmorilik 1978-79, May 1980, fig. 8.5.
15. Lead in Blue Mussel 
   Ibidem, fig. 8.9.
16. Lead content in the A- and Q-fjords. 
   From Asmund and Glahn: Miljøundersøgelser ved Maarmorilik, April 1985, fig. 5.
17. Lead concentration in wolffish liver. 
   From B.C. Research: Sampling at Maarmorilik,
The Agardhikaua fiord separating the Angel Mountain from Marnenik
LEAD CONCENTRATION IN THE WATER AT STATION 4 IN A-FIORD

4.
1. HYDRODYNAMICS OF THE FJORD SYSTEM
2. CLOSING A-FJORD WITH A DAM
3. REDUCTION OF METAL CONTENT IN TAILINGS
4. COMBAT AGAINST METAL SOLUBILITY
5. DISCHARGE SYSTEM FOR TAILINGS
6. ADDITIONAL POLLUTION SOURCES
7. SOME ANALYSES OF BIOLOGICAL MATERIAL
8 CONCLUSION

5.
6.
SUMMER

Q₁

Q₂

Q₃

Q_F FRESH WATER

Q₁ WIND DRIVEN CIRCULATION

WINTER

Q₂ SALT WATER INTRUSION

Q₃ VERTICAL CIRCULATION

7.
DAM 1a
TIME NEEDED 2 1/2 y
COST 50 TO 93 Mio DKR (1978)

DAM 4b
TIME NEEDED 2 1/2 y
COST 31 TO 72 Mio DKR (1978)
LEAD IN TAILINGS

0.5 %

LOSS OF LEAD IN TAILINGS
PER CENT OF LEAD CONTENT IN ORE

9.
SOLUBLE METALS IN TAILINGS
Metals in Bottom Water from the A-fjord

11.
CONCENTRATION OF Pb IN CETRARIA NIVALIS AS A FUNKTION OF THE DISTANCE FROM A POINT IN MAARMORILIK

12.
LEAD IN SEAWEED 1978

200 ppm Pb

975
LEAD IN BLUE MUSSELS 1978
TONS LEAD

1975 1980

LEAD CONTENT IN A AND Q FJORD

16.
LEAD CONCENTRATION
IN WOLFFISH LIVER

![Graph showing lead concentration in wolfish liver from 1978 to 1984.]

10 ppm Pb


-5

17.
ERRATA

Page 137: The caption for Fig. 5 should read:
"... at \(-2^\circ\)" instead of "... at \(-20^\circ\)"

Page 208: Fig. 1: The frame in the first figure shows Thule district, not Maarmorilik which is located further south at \(71^\circ\)N.

Page 270: Lines 2 and 3 of the text should read:
"... have confirmed the presence ..."

Page 277: Lines 1 and 2 of Chapter 4 should read:
"When the experimental results are applied we can formulate a simple model ..."

Page 984: First textline after equation (1) should read:
"that means minimum for horizontal increasing ..."

Page 985: Lines 12 and 13 should read:
"If \(\mu = 0.3\) \(\tan \alpha = 3.4\) or \(\alpha = 16^\circ\) (hor. \(90^\circ\))
- \(\mu = 0.1\) \(\tan \alpha = 10\) or \(\alpha = 6^\circ\) (hor. \(90^\circ\))"
SOUVENIRS
Banquet - Chief Engineer S.V. Hast and Captain J. Ladegaard of M/S "Disko"

Banquet with folklore entertainment by Silamiut Theatre Group
Arctic Hotel, Narssarssuaq

POAC 85 Secretariat
Opening Session: Tom Høyem, Minister for Greenland

Opening Session: Jonathan Motzfeldt, Premier of the Greenland Home Rule
Entertainment during Opening Session by Narssaq Choir

From left: Per Bruun, originator of POAC,
Per Tryde, Vice President of POAC 85,
and William Sackinger, President of POAC 85.
G. Frankenstein, invited speaker from CRREL, U.S.A.

V. Mikhailichenko, Ministry of Merchant Marine, U.S.S.R.
W. Sackinger, President of POAC 85

P. Tryde, Vice President of POAC 85
Banquet with folklore entertainment by Silamiut Theatre Group
Y. Kubo, C.R. Eng. Lab., Inc., Japan, speaking in Greenlandic

M. Christensen of Greenland Home Rule
Banquet with folklore entertainment by Silamiut Theatre Group