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In accordance with the Agreement on Scientific Cooperation Between the National Academy of Sciences (NAS) and the Academy of Sciences (ASUSSR), the "Workshop on the Mechanics of Ice and Its Applications" was held in Moscow and Leningrad, USSR from June 16-26, 1991.   Dr. Wilford F. Weeks, a member of the National Academy of Engineering and a professor at University of Alaska at Fairbanks served as the American chair.   Upon the completion of

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REPORT ON THE
NATIONAL ACADEMY OF SCIENCES-
ACADEMY OF SCIENCES OF THE USSR
WORKSHOP ON THE MECHANICS OF ICE AND ITS APPLICATIONS
JUNE 16-26, 1991

Prepared By:

Wilford F. Weeks, Chair of NAS Delegation
Geophysical Institute
University of Alaska

Edited By:

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This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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PREFACE

In accordance with the Agreement on Scientific Cooperation Between the National Academy of Sciences (NAS) and the Academy of Sciences (ASUSSR), the "Workshop on the Mechanics of Ice and Its Applications" was held in Moscow and Leningrad, USSR from June 16-26, 1991. Dr. Wilford F. Weeks, a member of the National Academy of Engineering and a professor at University of Alaska at Fairbanks served as the American chair. Upon the completion of the workshop, the NAS requested comments from Dr. Weeks on the quality of the program and the state of the scientific field. The following is a summary of his report based on his own personal observations. Though Dr. Weeks has incorporated information included in trip reports from individual participants, the views expressed herein are those of Dr. Weeks only and do not necessarily represent the views of the individual participants or sponsoring organizations.

CONTENTS

I. BACKGROUND

The United States and the former Soviet Union have strong common interests in obtaining a better understanding of the behavior of ice at all scales. In particular, Russia and the United States have vast resources in the North, notably off the shelves of Alaska and Siberia. In order to safely and economically exploit these resources, both countries require an in-depth understanding of the movement of the ice cover, the forces which moving ice can exert against bottom founded structures, and the ice resistance on vessels used to transport these resources to market.

Unfortunately, because of funding and personnel constraints, American progress in ice mechanics and engineering has been limited. In the opinion of the American delegation chair, Dr. Wilford Weeks, this 1991 Soviet-American Ice Mechanics Workshop demonstrated that considerable benefit can be gained by the United States and the former Soviet Union through collaboration in research programs and exchange of technical information. The United States can certainly benefit from the strong analytical skills of its counterparts in the former Soviet Union and the experience they have gained in successfully operating in northern rivers and along the Northern Sea Route. The scientists in the former Soviet Union can equally benefit from the application of American equipment and computer technology in solving ice engineering problems. In short, while resources are limited in the field of ice mechanics, the capabilities of the United States and the former Soviet Union complement each other well. An effort should be made so that these countries may work together in this area.

The goal of the Ice Mechanics Workshop was to facilitate the exchange of technical information between the United States and the Soviet Union. Although specialists in both countries had made great efforts to keep abreast of each other's achievements, the exchange of ice technology between the two countries could be characterized as poor. This was primarily due to language barriers and constraints on communication and distribution of literature. Often, several years went by before American specialists learned of a significant discovery made by their Soviet counterparts.

The participants at the workshop addressed a number of themes, ranging from the behavior of ice at the microscale to the large-scale dynamics of the polar

pack. The participants discussed both long-range research items and short-term applied ice engineering practices. The diversity of the workshop reflected the varied background of the delegates.

1. <u>Mechanical Properties of Ice</u>: A number of papers were presented dealing with the mechanical properties of ice, including uniaxial compression and tension, and confined compression, bending, and fracture toughness. Data on the mechanical properties of ice were considered. Additionally, testing techniques and documentation of appropriate ice properties were addressed.

2. <u>Ice dynamics and processes</u>: Large-scale ice dynamics and processes were considered including the acquisition and application of satellite imagery; large-scale properties of the ice cover such as floe size and lead patterns; pressure ridge processes and models; ice stress measurements; bearing capacity of ice sheets; mechanical profile properties; and sea ice dynamics models which describe and predict the overall behavior of the ice cover.

3. <u>Ice-structure interaction</u>: Ice forces on offshore structures were reviewed. Presentations were given on practices employed in the United States to derive ice design criteria. Specific topics included the determination of local, global, and impact ice loads. The results of model basin ice indentation tests were also presented and discussed.

4. <u>Modeling ice behavior</u>: Considerable attention was focused on modeling ice behavior at small scales. Constitutive models were presented which describe the behavior of ice during creep and brittle fracture for both polycrystalline ice and single ice crystals.

5. <u>Perspectives on ice mechanics and engineering</u>: All of the participants from both the United States and the Soviet Union obtained an interesting and comprehensive perspective on ice mechanics and engineering not only in their respective countries, but in the world. The American delegation, drawn from academia, government laboratories, and industry, included the top researchers in ice mechanics in the country. Through formal presentations, panel discussions, and informal gatherings, the participants acquired a

greater awareness of the state of the art, and obtained a consensus on the important problems.

6. Education and training of ice engineers: Inclusion of representatives from academia and industry permitted fruitful discussions on the education and training of ice engineers. Topics included the present demand for ice engineers and the adequacy of the training which potential engineers and scientists will need to receive to meet the future needs of industry and government.

II. GENERAL OBSERVATIONS

[In this report, some information is included that is based upon discussions between the American delegation chair Dr. Wilford Weeks and Dr. Anatoly Frolov, an expert on permafrost. Dr. Weeks met Dr. Frolov in the late 1970's when he was a visiting scientist at USA Cold Regions Research and Engineering Laboratory (CRREL) in Hanover, New Hampshire. Just prior to the meeting in the Soviet Union, Dr. Frolov was hosted for three weeks by Dr. Weeks in Fairbanks, Alaska. Later, while Dr. Weeks was in the Soviet Union, he had the opportunity to visit with Dr. Frolov on two different occasions.]

The National Academy of Sciences (NAS) - Academy of Sciences of the USSR (ASUSSR) Workshop on Ice Mechanics was conducted in the Soviet Union in June 16-26, 1991. Preparations for this workshop were initiated when the ASUSSR suggested that a workshop on this topic be included in the larger program of bilateral activities on technical topics sponsored by the two academies. These activities were to be carried out within the framework of the Workshop provision (Article III) of the Agreement on Scientific Cooperation Between the National Academy of Sciences of the USA and the Academy of Sciences of the USSR signed January 12, 1988. The interacademy Protocol of January 31, 1990 called for this specific workshop.

The meeting offered a rare opportunity to gain insights into a research area in which the Soviets, historically, have had a strong presence and in which there has been little interaction between American and Soviet specialists. (There are

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interesting reasons behind this pattern which will be discussed in a later section of this report.)

The subject of ice mechanics is quite broad, encompassing the mechanical behavior of glacier, lake and sea ice. The Soviet Union possessed strong research programs in all these subjects for years, with the total number of scientists and engineers involved far exceeding its equivalent number in the West. The reason for the Soviet interest in these fields is clear: the USSR had significant applied problems in the snow and ice area. This country also had extensive experience in effectively alleviating a large number of such problems. The amount of contact between Soviet and Western scientists in the different sub-areas of ice mechanics has been quite varied, with contacts in the area of glaciers and large ice sheets and shelves being reasonably common. This area of ice mechanics was largely carried out within the Department of Geography of the ASUSSR (now, the Russian Academy of Sciences). Its focus was generally pure science with little immediate application. (Recently though, the climatic aspects of ice cores have achieved considerable interest within the world climate community). It should also be noted that much of this work was focused on the Antarctic.

Soviet researchers in other aspects of ice mechanics, and those active in sea ice studies in particular, have had considerably less contact with the West. In fact, over a 36-year period, Dr. Weeks has had the opportunity to meet only three or four Soviet ice mechanics specialists. This isolation has been particularly true for scientists from the largest organization active in Soviet sea ice research, the Arctic and Antarctic Research Institute (AARI) in St. Petersburg. Similar remarks, however, might be made concerning other smaller groups that carry out programs in lake and river ice research.

Why is this the case? In the sea ice field, the answer appears to be obvious. Groups that have a thorough understanding of sea ice mechanics have a definite advantage in analyzing certain scientific problems related to climate change in the polar regions. More importantly, understanding sea ice mechanics is necessary to understanding the effects of ice forces on offshore structures – a problem that is essential to the safe development of the large oil and gas reserves that are presumed to lie beneath the pack ice on the continental shelf

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of the Arctic Ocean. (The former Soviet Union's continental shelf is the largest in the world. Its potential for major oil and gas production is believed to be extremely high.) Of particular interest here is the Northern Sea Route, a critical supply line to ports in the northern parts of the former Soviet Union. Since this route transits the margins of the Arctic Ocean, ice is a major problem during most of the resupply season (This activity has developed into an almost year-around operation over the past few years.)

Even more important, however, is the fact that the understanding of sea ice properties and behavior was very important to the submarine arm of the Soviet Navy. In recent years the Soviet Navy developed a unique strategy (the so-called Arctic Bastion Strategy) concerning the deployment of their missile-launching submarines (SSBNs). Descriptions of the general aspects of the Soviet bastion strategy have recently been published in journals such as <u>Janes</u>. In accordance with the Arctic Bastion Strategy, the Soviets deployed their SSBNs underneath the pack ice, where once on station, they were able to reduce their noise-making activities. Becoming essentially invisible in acoustical terms, the SSBNs would wait for a message to launch their missiles. If so instructed, they would only have to move to the nearest open lead to launch their missiles. It should also be noted that sea ice lessens the effectiveness of almost every type of anti-submarine system. Thus, locating submarines that are deployed according to this strategy becomes very difficult.

Perhaps the most important consideration when discussing Soviet ice mechanics research is that the Soviets viewed the ice covered seas to their north as an integral part of their territory. This is the so-called pie theory of the Arctic, with the very large Soviet part of the pie extending all the way to the North Pole. Thus, when one starts discussing arctic sea ice research, one is indirectly dealing with capabilities that in the Soviet view related to vital economic routes, problems of naval security, and territorial prerogatives. Since the Soviets viewed their capabilities in the arctic seas to be superior to those of the Western countries, they were not eager in the past to undertake joint research in fields such as ice mechanics. The Soviet scientists working in these fields were rarely allowed to attend scientific meetings outside the USSR, nor to develop cooperative programs. Therefore, the Soviets' list of suggested topics

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for this workshop created an uncharacteristic opportunity to discuss subjects that are directly applicable to ships operating in ice, to natural mechanical processes in sea ice covers such as ridge and rubble formation, to ice forces on offshore structures, to techniques for modeling ice behavior, and to more fundamental aspects of the deformation and fracture of ice.

Some of the Soviet workshop participants contributed to this unusual atmosphere. For instance, Dr. G. A. Lebedev's group from AARI is known to be heavily involved in aspects of the geophysics of sea ice that were of direct applicability to the problems of the Soviet submarine fleet. (Dr. Lebedev is the successor to Dr. V. V. Bogorodski who died of a heart attack a few years ago. Dr. Bogorodski was an extremely prolific, high quality scientist who contributed to acoustic, remote sensing, ice property and ice penetration research. Members of his group such as Dr. V. P. Gavrilo are outstanding.) Although Dr. Lebedev himself is not as well known as the other members (to date he has not published as extensively), he nevertheless appears to be quite capable. During the workshop, he was present whenever policy matters were discussed, raised interesting points during the discussions, and expressed much interest in joint research programs.

Two of the other Soviet groups which participated in the workshop also had obvious ties to the Soviet navy: the Krylov Ship Research Institute (with its extensive model basins) and the Leningrad State University of Ocean Technology (which trains naval architects and engineers - many of whom eventually work on or with submarines). These topics will be addressed in further detail later in this report.

III. WORKSHOP

During the Ice Mechanics Workshop, four days were strictly devoted to presentations. The American presentations were quite varied with heavy emphasis on experimental and numerical modeling. Importance was placed on real-world observations and real problems - not surprising in that the U.S. delegation contained several scientists from oil companies, as well as contractors, who had experience with offshore operations. In contrast, the Soviet presentations were

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generally heavy on theory and analytical procedures. Consequently, many of the approaches appeared to be somewhat unrealistic, especially when closed-form solutions were offered. (This was commonly accomplished by setting up problems that were artificial from the start.) Given limited computing capabilities and the fact that the Soviets have historically been leaders in finding such closed-form solutions, many of the Soviet authors appeared to be reluctant to consider actual field conditions. Moreover, the expertise of the Institute of Mechanical Problems (IW) of the ASUSSR (now, the Russian Academy of Sciences) lies with theory. The result was that some of the Soviet ice dynamic presentations used approaches that already had been tried and dispensed with in the West.

At the meeting, communications were sometimes strained given the difficult job of interpreting. Interestingly, whereas most of the American participants did not speak Russian, a few of the Soviets spoke excellent English and many of them appeared to have some understanding of the language.

IV. MEMORANDUM OF COOPERATION

At the start of the meeting, Dr. K. V. Frolov, vice president of the ASUSSR (currently a vice president of the Russian Academy of Sciences), stressed that it was important to form a permanent US/USSR committee on the subject of ice mechanics and climate. He felt that this was a subject of importance to both countries that required significant additional research. He hoped this permanent committee would develop a system of projects and grants in a manner similar to that of the Soviet-Swedish joint program. He added that ice mechanics research needed improved visibility and financing even in the Soviet Union. As an aside, Dr. Frolov suggested to Dr. Weeks that a letter be written to the National Academy of Sciences and to the National Science Foundation about these opportunities, and that a copy of any such letter be given to him.

On the second day of the workshop, several of the American participants were called into a short meeting in the Office of the Director of IW concerning the writing and signing of a joint memorandum. In this meeting, and in the memorandum meetings that followed, Dr. Igor Vasiljev, who appeared to have considerable experience with such arrangements, represented the Soviet delegation and

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Dr. Goldstein the American delegation. Although the American workshop participants stressed that they did not have the authority to make commitments on behalf of the NAS or any U.S. government organization, the Soviets thought that this memorandum was still most important. (See Appendix.)

It was agreed, however, that cooperative work was in everyone's best interest and that everything possible that could be done to support this initiative should be done. The representatives of the oil and gas companies at the meeting were very positive and gave strong support to such a memorandum. Moreover, they stated that they would be able to provide at least partial financial support for the activities of the proposed committee, which would be composed of five scientists from each country. The experience could be illuminating for both sides.

V. SITE VISITS

Krylov Ship Research Institute

Founded in 1894, Krylov is extremely large in size and scope. Evident by the variety of models of warships on display, this institute did considerable work for the Soviet Navy. Its projects vary widely and deal with modeling, nuclear powered ships, deep-sea submersibles, hydrofoils, and hovercraft. The institute also works for foreign firms and is interested in acquiring additional foreign business. Moreover, Krylov offers short-term seminars (2-3 days) on specific subjects and is considering making these lessons available to foreigners. In addition, it appears that the institute conducts investigations that contribute to specific ship designs, but does not do the actual designs itself. Similarly, Krylov conducts investigations of materials, though it does not develop new materials. Krylov's staff includes 60 Ph.D.s and approximately 500 D.Sc.s.

Though the NAS delegation toured some open water basins and Krylov's ice tank, only the latter will be discussed. The head of the ice model basin, Dr. Valery Belyashov, gave the primary presentation. According to Dr. Belyashov, the institute uses saline ice to simulate natural sea ice, and recently has been focusing on problems relating to propeller design for icebreakers. The Soviet presentations on this subject were very impressive and the analysis very sophisticated. The American group was not aware of similar work on propellers being undertaken in the West. The facility itself was in good shape and was being

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extensively used. However, it should be noted that the data logging equipment appeared to be old and outdated by approximately 20 years.

It would be very interesting for Western industry to give Krylov a small testing contract to see how easy it would be to work together. There may be problems with secrecy, as this was the one laboratory where pictures were not allowed to be taken. If a decision relates to the collection of data in sensitive areas (such as the seas north of the Russian mainland), Dr. Nikolay P. Laverov should be addressed. Dr. Laverov served on the Cabinet of Ministers of the USSR and the State Committee on Science and Technology of the USSR. At the time of this workshop, he was also the Chair of the Commission on Arctic Problems of the Academy of Sciences of the USSR. According to Dr. Frolov,
Dr. Laverov is the senior official who clearly has the authority to make such decisions. As a geologist, Dr. Laverov can understand the technical issues involved in such projects. In this case, the difficulty is in trying to meet with such a highly placed individual.

In the future, a serious attempt should be made to develop a significant joint program with Krylov. The institute has both the data and the experience. The Krylov scientists would seem to welcome a program such as this, and the American scientists would learn much in this area. The cooperation would not be easy to arrange, but it certainly could be worth the effort. However, some care would clearly have to be taken to minimize the concerns of all parties.

Leningrad St. te University of Ocean Technology
This university trained most of the Soviet naval architects and engineers. The Rector of the University gave a fascinating talk regarding his institution. The university has specialists in five main areas:

1) **general studies** (math, physics, materials, chemistry),
2) **shipbuilding/ocean engineering**,
3) **machinery**,
4) **electronics** (the largest group),
5) **management and economics**.

Its budget is about 30 million rubles, of which two-thirds comes from the state. The outside funding of 10 million rubles comes from the military (10%) and from industry (90%). (Most of this money is not for science.) Recently, the support for basic research has been drying up. The university used to have, roughly stated, 3 million rubles for basic research, but now has only one-tenth of that amount. The rector also expressed concern about losing the best of the university's staff members. [The university currently has 50 chairs, 78 full professors (D.Sc.) and 300 Candidates of Science.]

Having foreseen these financial difficulties, the university cut its student body from 1225 per year to 750 per year. At present, the institution graduates only about 500 students per year. A large percentage of its graduates in the past went to work designing and building submarines, but now that the demand for this is low, there is no need for as many graduates. The rector stated, "We would design one and they would build one or two of them, and the next thing you know they wanted another design. That took a lot of people. However two to three years ago, the order book for new submarines went to zero; thus, we figured that the demand for our graduates would be less and we started cutting back." The university has now started its own enterprise by producing items invented by faculty members. The rector appeared to be rather pleased with these activities which were showing considerable promise and profit.

The rector appeared to be very interested in developing cooperative work with U.S. universities and companies. Presently, the university has a program underway with Worcester Polytechnic Institute in Massachusetts (WPI). In this program, WPI sends students in the social sciences and languages to Leningrad State University, which, in turn, uses the hard currency obtained from this exchange to support its science and engineering professors when they spend sabbaticals at WPI. Clearly, the rector wants his staff to go abroad to broaden their interests and to increase their knowledge of the latest technology. On the other hand, he does not want lose all of his best people. He feels that the university is in a crisis situation at present, and that it will be difficult both to survive and to maintain high standards. His vision of the university's research emphasis during the next 5 years is as follows:

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1) **materials** (special steels for reactors, improved equipment and technology for nuclear stations to enhance their reliability, materials with shape memory),

2) **modeling of processes** [The university needs better computer facilities and better and more specialized software.],

3) **semiconductors for acoustics**,

4) **geophysics** (studies at 0.1 to 0.2 Hz) [This work was started for the military, but is now believed to have some important civilian applications.],

5) **propulsion** (with emphasis on reducing noise),

6) **new power systems** utilizing hydrogen,

7) **electronics** [Roughly one-third of the university is focused on this at present.].

From this list of research topics, it is clear that the university was still performing significant work for the Soviet Navy.

After the rector's presentation, the NAS delegation group was given a facilities tour by Professor L. I. Slepian.

Arctic and Antarctic Research Institute (AARI)

This 70-year old institute with a staff of 2,000 runs six ships, several Antarctic research stations, and one to two drift stations in the Arctic Ocean. (It is housed in a relatively new building of at least ten stories.) The American delegation found AARI, which belongs to the Hydrometeorological (Gidrometeorolzdat) Ministry, to be quite different from the universities and the institutes of the Academy of Sciences. Dr. Y. E. Nikiforov, Assistant Director of AARI (himself a theoretician who works in numerical modeling) and Dr. Sergey Karpekin, Deputy Director of AARI, addressed the delegation. Dr. Nikiforov stated that the Soviets knew American results better than the American scientists knew the Soviet results. He also suggested that Soviet work (presumably in ice dynamics modeling) was better than the American work.

AARI's principal interests are ice as a material and the physical and mechanical properties and dynamics of natural ice covers. Research areas of particular interest to the institute also include the remote sensing of ice covers, relations between the structural and electromagnetic properties of ice,

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and the influence of ice on engineering structures including ships. (AARI works closely with the Northern Sea Route Administration.) In general, the institute's research approaches are similar to those of the West. The split between laboratory and field studies is roughly 50/50, but 80% of the funding goes to field programs because of the high cost of logistics.

Dr. Nikiforov answered a number of questions that were posed to him by the NAS delegation. An interesting exchange took place and is summarized as follows:

Q: **Is AARI interested in information exchanges?**

A: Yes, but such exchanges must be specified in a joint agreement. AARI has similar bureaucratic problems to organizations in the U.S.

Q: **Is the fact that AARI belongs to the Hydrometeorological Ministry important?**

A: Yes. To deal with AARI, it is probably necessary to sign a separate agreement with the Ministry. Without this step, it is doubtful that AARI would receive the funding necessary to honor the agreement. [It was implied that an agreement with the ASUSSR did not carry much weight with Gidrometeorolzdat.]

Q: **Would you consider undertaking a joint research program on ice fracture and acoustic noise?**

A: No.

Q: **Do you have detailed information on sea ice conditions in the Soviet seas?**

A: Yes. However, we cannot release such information to you without specific permission from our Ministry.

Q: **During recent years AARI has commonly operated two drifting stations in the Arctic Basin. At present, only one station is operating. Do you plan to operate one of two stations in the future?**

A: We have cut back to one station because of funding limitations. [This left the opportunity for AARI to return to two stations when it can afford it.]

Q: **Recently there have been several papers published in the Western literature which have examined the extent of the arctic ice pack to see if there are any temporal trends that could be associated with a greenhouse effect. Based on your extensive experience, have you discovered any systematic decrease in overall sea ice extent in the Arctic?**

A: No. However, the variations from location to location and from year to year are very large.

Q: **Which is easier, joint work in the Arctic or in the Antarctica?**

A: Joint work in the Antarctic is much easier. [In fact, a joint U.S./U.S.S.R. drift station is planned for the Weddell Sea during 1992. Recently, NSF has signed a cooperative agreement with the Soviets for work in snow and ice engineering related to the operation of stations in the Antarctic. This should be contrasted with the fact that U.S. scientific parties, which were planning to utilize a Soviet icebreaker cruise from Murmansk to the Bering Strait via the North Pole, have been informed that no science can be carried out on the cruise. This is despite the fact that the cruise was a Soviet initiative with a ticket price of roughly $20,000 for each U.S. investigator and that the details of the U.S. science program had been known to the Soviets for some time.]

Following this discussion, the NAS delegation toured the AARI ice tank. The tank, which like Krylov uses salt ice to simulate sea ice, is only two years old. It is the successor to AARI's original tank (which was apparently the first ice tank in the world). The tank dimensions are 40 meters by 5 meters by 2 to 7 meters (in depth). The Soviets can freeze the ice at two different rates depending upon whether they use the cooling coils on the ceiling (slow freezing) or a covering system which provides an air temperature of roughly -25 degrees C. Once the required ice thickness is achieved, the scientists warm the room's temperature to get the proper values for the ice strength and elastic modulus.

Though Dr. Nikolaev is apparently in charge of the tank, Dr. Vladimir Likhomanov gave the presentations. There was no ice in the tank when the NAS delegation visited the premises.

Although apparently new, the tank did not appear to be in the best condition. Dr. Weeks asked about the Soviet experience with using salt. (Western laboratories have largely discontinued its use because of severe corrosion problems). The Soviets replied that they used special rust-proof materials and therefore did not anticipate such problems. (It was noted, however, that there was already thick rust present all over the tank.) There was an impression that the Soviets had not used this tank a great deal, and one of the Soviet specialists confirmed that they did not have many requests for studies. Comparatively, the

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AARI tank did not seem to be as impressive as the Krylov facility.

The NAS delegation could have easily spent more time at AARI. There was unfortunately no opportunity for a visit to the ice reconnaissance group that is located on the eighth floor of AARI. This group has experience operating a sea ice thickness radar with reportedly very impressive results. But even during the brief visit, some interesting discussions were carried out with Dr. Gavrilo regarding remote sensing. Dr. Lebedev's group clearly wants to become involved in a cooperative ice structure-ice properties (electrical and mechanical) remote sensing program. In fact, Dr. Lebedev specifically stated this desire. As a result, Dr. Weeks plans to propose such a cooperative program including a joint field operation. Dr. Weeks maintained that this type of program would not be easy to arrange even with the best will on both sides, since many people in addition to the scientists must approve American-Soviet cooperation in this field. He added that perhaps this kind of cooperation could only be accomplished in the Antarctic. Nevertheless, he believes such an initiative should be attempted.

There is little doubt that AARI is where the real experience lies concerning Soviet research in ice structure, ice properties, and ice applications of remote sensing. In the area of offshore design, the expertise appears to be more diffuse. This is particularly true as the result of the recent death of Dr. Kheisin who was AARI's top expert on this subject.

Leningrad State Technical University

This university, which has graduated 140,000 engineers, houses several different institutes and 56 departments. Its staff includes 7 academicians and 12 corresponding members of the Academy, 2,000 teachers, and professors (1,100 Ph.D.s and 250 D.Sc.s). The current student body is composed of 20,000 students including 1,200 foreign students. Approximately one-third of its program is conducted in the evening. The university largely responds to the plans of the Academy of Sciences. In the past, the government only required that the university prepare students and conduct research. Now, in addition to its other tasks, the university must carry out business operations since it does not receive adequate funding from the State.

Professors Shkhinek, Simakov, Rosen, Sokolov and Bogolov gave presentations to the NAS delegation that were largely focused on theoretical considerations.

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Professor Rosen stated, "Our mathematics is the best in the world and we are very inexpensive to support with foreign currency." The latter part of his statement is unquestionably correct. At present, working scientists get paid 3000-4000 rubles per month, which at the September 1992 exchange rate of 215 rubles per dollar, equals approximately $18.60 per month.

The NAS delegation went on to tour some of the laboratory facilities which were generally in the field of ocean engineering and were not that advanced by Western standards. There was no doubt that the professors to whom the NAS delegation talked were very interested in cooperative work of any type.

VI. CONCLUSIONS

Evidently, Russian universities and institutes [that have come under the purview of the ASUSSR] have been told to make Western contacts and to undertake joint programs for the purpose of obtaining hard currency. They are trying hard to do just this in order to pay for their scientists and necessary supplies. The transition to a more open economy, however, is going to be particularly difficult for the research community in the former Soviet Union. There seems to be a common Soviet misconception that American scientists are extremely well funded. When Dr. Frolov visited University of Alaska at Fairbanks, for example, he initially seemed to think that additional research funds could be easily obtained. Considerable effort was undertaken to explain the real situation in U.S. science. He expressed surprise and amazement at the recent reports on Fairbanks' funding levels and patterns. Dr. Frolov and his knowledge of the U.S. science structure seems to be the exception. The vast majority of Soviet scientists whom the NAS delegation met while in the USSR appeared to hold unrealistic expectations of the possibilities for U.S. support for Soviet science. On a similar note, the Soviets may not understand what would be expected of them should they receive such funding. (This would be especially true if they were to receive funding from private companies where instant performance is assumed and where company engineers look over their researchers' shoulders.)

The level of output of Soviet scientists was different than the level in the United States. This was exemplified by visits to large Soviet organizations that

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employ far more scientists in the general area of ice and snow research than are employed in all U.S. and European institutions combined together. The output of these Soviet groups was small, and in many cases not as groundbreaking as it could be, given the fact that some of the key issues in the field were not being addressed. (Many Soviet papers would not have been approved by peer reviewers in the West.) However, in the most recent publications of AARI, there has been a significant change. The papers have started presenting details with charts, tables, graphs and maps. This academic approach is an encouraging development.

In their efforts to secure hard currency, the different Soviet organizations are clearly in head-to-head competition with each other. If one wishes to arrange a cooperative study with a theoretician or an experimentalist at either a university or an Academy institute, a few problems would most likely arise. The most difficult problem would probably be to obtain funding. (In this area, the one exception among the institutes that were visited by the NAS delegation was AARI. This may simply be because AARI is in a government ministry.) Given the political and military sensitivity of the Arctic Ocean and its peripheral seas, the possibilities of joint research is complicated. Another problem is that scientists never seem to have the opportunity to directly discuss the research issues with the people who have the ultimate decision making authority in these areas.

It is worth noting that the final sentence in the second paragraph of the memorandum of cooperation is as follows: "It is further suggested that the U.S. National Science Foundation and U.S.S.R. Academy of Sciences add the subject area of ice mechanics to its approved list, 'Scientific Problems of the Arctic and the North' that are considered as appropriate for U.S.-U.S.S.R. cooperation in the field of Basic Scientific Research." Although it was repeatedly pointed out that NSF had removed the restrictions on subjects that could be considered under this program, the Soviets were adamant that such a statement be included. They had evidently found such restrictions to be a hindrance in the past.

The NAS delegation attempted to make the memo as flexible and as simple as possible. It was generally felt that activities carried out under the memo would be focused and implemented by small groups of specialists. It was also apparent

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that the Soviets felt that the memo would make it easier for their institutes to interact with American oil companies. The hope was to have the memo signed by the time the NAS delegation left the U.S.S.R., but this did not prove to be possible.

The poor maintenance and construction of the Soviet institutes contributed to the overall gloomy mood of the Soviets scientists. The next few years will undoubtedly be difficult for scientists in the former Soviet Union. Mutually advantageous scientific exchanges and joint research programs would clearly aid the science community in the former Soviet Union. It is the opinion of the American delegation chair that, in areas such as ice mechanics where the Soviets have had so much experience, well designed research collaboration could be very beneficial scientifically and even cost effective for the United States. Such joint programs should receive significant support. In the future, the return on these possible U.S. investments could be very substantial.

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WORKSHOP ON ICE MECHANICS AND ITS APPLICATIONS

Each working day the sessions were held in two time blocks. The first block occurred in the morning usually between 09:30 and 13:00, followed by a lunch break, with the second block starting at 15:00.

MONDAY, JUNE 17

OPENING OF WORKSHOP

10:00 - 11:00   **Introduction**

Speakers: K.V. Frolov, Vice President, ASUSSR

D.M. Klimov, Corresponding Member, ASUSSR;
Director, Institute for Problems in Mechanics

W.F. Weeks, Member U.S. National Academy of Engineering;
Professor of Geophysics, Geophysical Institute;
University of Alaska at Fairbanks

V.V. Mikhailichenko, Head of Northern Sea Route
Administration, USSR Ministry of Merchant Marine

11:00 - 11:30   **Mathematical Modeling of Large-Scale Floating Ice Motion**

Speaker: S.S. Grigorian

11:30 - 12:00   **Interrelations Between Growth Conditions, Sea Ice Structure, and Sea Ice Properties**

Speaker: W.F. Weeks

12:00 - 14:00   Lunch

MECHANICAL PROPERTIES OF ICE. DEFORMATION AND FRACTURE.
Chairs: S.S. Grigorian and W.F. Weeks

14:00 - 14:30   **Deformation and Fracture of Ice**

Speakers: R.V. Goldstein, V.P. Epifanov, and N.M. Osipenko

| 14:30 - 15:00 | Fracture Behavior and Size Effect |
| | Speaker: J.P. Dempsey |

| 15:00 - 15:30 | Crack Propagation in Ice Cover under the Action of Moving Normal Load |
| | Speakers: A.V. Pushkin, L.I. Slepian, and A.N. Zlatin |

| 15:30 - 16:00 | Break |

Chairs: N.S. Solomenko and A.D. Kerr

| 16:00 - 16:30 | Modeling the Brittle Compressive Failure of Ice: Possibilities and Implications |
| | Speaker: W.A. Nixon |

| 16:30 - 17:00 | On the Question of Physical Properties of Sea Ice |
| | Speakers: V.A. Borodkin, V.P. Gavrilo, S.K. Kovalov, G.A. Lebedev, and V.V. Pasynkov |

| 17:00 - 17:30 | Prediction of the Mechanical Properties of Undeformed First-Year Sea Ice During the Growth Season |
| | Speaker: G.F.N Cox. |

TUESDAY, JUNE 18

ICE COVER MECHANICS
Chairs: L.I. Slepian and D.E. Nevel

| 09:30 - 10:00 | Bearing Capacity of Ice Covers Subjected to Static and to Oscillatory Loads |
| | Speaker: A.D. Kerr |

| 10:00 - 10:30 | Problems Related to the Static Strength of Ice Cover |
| | Speakers: B.G. Korenev and E.B. Koreneva |

| 10:30 - 11:00 | The Mechanics of Pressure Ridge Building from a Wide Viscoelastic Plate |
| | Speaker: M.D. Coon |

11:00 - 11:30   Break

                Chairs: G.A. Lebedev and G.F.N. Cox

11:30 - 12:00   **Numerical Simulation of the Drift of a Variable Thickness Ice Cover in the Arctic Ocean**
     Speaker: S.A. Kolesov

12:00 - 12:30   **Sea Ice Dynamic Models**
     Speaker: R.S. Pritchard

12:30 - 13:00   **A Model of Drift-Ice**
     Speaker: A.V. Marchenko

13:00 - 15:00   Lunch

                            ICE LOADS
                Chairs: N.G. Khrapaty and R.L. Brown

15:00 - 15:30   **The Ice Research Programs and Experimental Facilities of the Krylov Ship Research Institute**
     Speaker: V.M. Shpakov

15:30 - 16:00   **Probabilistic Ice Forces**
     Speaker: D.E. Nevel

16:00 - 16:30   **Simulation of Ice Loads on Ship Hulls and Off-Shore Structures**
     Speakers: (D.E. Kheisin), V.A. Kurdyumov, and V.A. Likhomanov.

16:30 - 17:00   **Ice Loads on Structures - A Case Study**
     Speaker: A.T. Wang

17:00 - 17:30   **The Mathematical Modeling of Ice Interaction with Vertical Piles**
     Speakers: D.G. Matskevitch and K.N. Shkhinek

WEDNESDAY, JUNE 19

Cultural Program

THURSDAY, JUNE 20

ICE LOADS
Chairs: V.M. Shpakov and M.D. Coon

09:30 - 10:00   **Ice Loads on Off-Shore Structures (Investigations of the Leningrad State Technical University)**
       Speakers: G.V. Simakov and K.N. Shkhinek

10:00 - 10:30   **Dynamic Ice-Structure Interaction During Indentation Tests**
       Speaker: D.S. Sodhi

10:30 - 11:00   **Study of Ice Action on Offshore Structures**
       Speaker: N.G. Khrapaty

11:00 - 11:30   Break

Chairs: G.V. Simakov and S. Shyam-Sunder

11:30 - 12:00   **A Ship in an Ice Cover Under Compression**
       Speakers: R.V. Goldstein, V.I. Danilenko, P. Kujala, N.M. Osipenko, and P. Varsta

12:00 - 12:30   **Iceberg Impact Pressure and Force Design Criteria for Fixed Platforms**
       Speaker: A. Prodanovic

12:30 - 13:00   **Dynamic Ice-Flexible Structure Interaction Phenomenon**
       Speakers: S.A. Vershinin, A.A. Iliady, and A.B. Below

13:00 - 15:00   Lunch

MECHANICAL PROPERTIES OF ICE: DEFORMATION AND FRACTURE

Chairs: R.V. Goldstein and J.P. Dempsey

15:00 - 15:30   **Investigation of Ice and Clathrate Characteristics**
      Speakers: V.P. Larionov and E.A. Bondarev

15:30 - 16:00   **Mechanical Properties of Sea Ice: Laboratory Experiments**
      Speaker: J.A. Richter-Menge

16:00 - 16:30   **Some Recent Developments in Experimental Ice Mechanics at CRREL**
      Speaker: D.M. Cole

16:30 - 17:00   Break

Chairs: S.A. Vershinin and W.A. Nixon

17:00 - 17:30   **Modelling the Constitutive Properties of Sea Ice Single Crystals**
      Speaker: R.L. Brown

17:30 - 18:00   **Numerical Models of Ice Deformation**
      Speaker: S. Shyam-Sunder

FRIDAY, JUNE 21

ICE MECHANICS: VARIOUS PROBLEMS
Chairs: V.P. Larionov and D.S. Sodhi.

09:30 - 10:00   **Deformating of Ice Under Influence of Coming to Surface Rigid Body**
      Speakers: V.M. Alexandrov and A.A. Shmatkova

10:00 - 10:30   **Field Measurements of Pack Ice Stresses**
      Speaker: W.B. Tucker, III

10:30 - 11:00   **Ice Island Structures for Exploration Drilling**
      Speaker: D.A. Mirzoev

11:00 - 11:30   Break

                    Chairs: K.N. Shkhinek and A.T. Wang

11:30 - 12:00   **Instability and Self-Organization of Ice Sheets**
     Speaker: V.L. Mazo

12:00 - 12:30   **Sea Ice Mechanics in the Context of United States Arctic Marine Basic Research**
     Speaker: T.B. Curtin

12:30 - 13:00   **Definition of the Loading Regime on Offshore Structures from Drifting Ice Covers**
     Speaker: A.T. Bekker

13:00 - 15:00   Lunch

                          DISCUSSION

15:00 - 17:00   **Education and Placement of Cold Region Engineers**
     Speakers: J.P. Dempsey, N.G. Khrapaty, W.A. Nixon, K.N.
                 Shkhinek, S. Shyam-Sunder, G.V. Simakov, L.I. Slepian,
                 and P. Varsta

                    CLOSING OF THE WORKSHOP

17:00 - 17:30   Conclusion

SATURDAY, JUNE 22

Evening: Departure from Moscow to Leningrad by train

SUNDAY-TUESDAY, JUNE 23-25

Visit to Leningrad Institutes
- Arctic and Antarctic Research Institute
- Krylov Ship Research Institute
- Leningrad State Technical University
- Leningrad State Technical University of Ocean Technology

TUESDAY, JUNE 25

Evening: Departure from Leningrad by train

WEDNESDAY, JUNE 26

Day: Departure from the USSR
(Several participants departed via St. Petersburg.)

IX. ABSTRACTS

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DEFORMATING OF ICE UNDER INFLUENCE OF COMING TO SURFACE RIGID BODY

Deforming of ice by coming to surface rigid body has been studied. The problem of this kind may appear, for example, when protecting hydrotechnical constructions from the influence of an ice cover, because the mechanical destruction of ice with the help of rigid shiplifting pontoon may be one of the methods of protection.

The contact problems for the plates lying on the hydraulical base in the conditions of the cylindrical bend are considered. The plate is influenced by the smooth rigid stamp, which is pressed by the force from the side of liquid. The base of the stamp is described by the equation $y=f(x)$, where $f(x)$ is an even function. Side by side with the general case particular examples are considered: when $f(x) = -c*x$, $(c>o)$ is an exact analytical solution of the problem is received, when $f(x) = -c*x$ solution is received with the help of graphic-analytical exploration. The method of the solution is written and the program of the numerical realization of the problem is made up for the general case, when $f(x)$ is an arbitrary even function.

Different kinds of the physical picture of the problem are considered in the dependence on changing of the introduced dimensionless parameters, connected with bending rigidity of the ice plate, coefficient of the bed of the base, the density of ice, and free-fall acceleration. Complete solution is written and restrictions are imposed on the dimensionless parameters. The limits of changing of the value of the buoyant force in the dependence on changing of the physical characteristics of the ice plate, hydraulically based, and the form of the coming to surface body are given.

The next cases of a contact are explored in detail: 1) there is a contact

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between the coming to surface body and the ice plate at some section, further
there is the section of the ice plate, which has no contact with the hydraulical
base and then the section where the plate is lying on the hydraulical base; 2)
there is a contact between the coming to surface body and the ice plate at some
finite section and then there is a contact between the plate and the base; 3)
when the section of the contact between the coming to surface body and the plate
is turning practically into a point.

The expression for the bending moment is written and the cross-sections
where the bending moment achieves the maximum absolute values are shown.

The results of the work may be sued for the calculation of the capacity of
pontoon, providing breaking of ice covers. The corresponding axisymmetric problem
may be studied in the same way.

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DEFINITION OF THE LOADING REGIME ON OFFSHORE STRUCTURES
FROM DRIFTING ICE COVERS

The designers of offshore ice-resistant structures in ice covering seas need information not only about the extreme ice forces but about the middle values too. Also one needs information about the ice force variance during life time for structures and their element reliability analysis.

This problem may be solved by modelling of ice force as a stochastic process. Investigation of process parameters with the help of physical modelling is difficult and needs a long time to work. So it is clear to use the mathematical node good way. The method of statistic modelling theory was used considering the stochastic nature of main parameters change which influences drifting ice cover-structure interaction. An imitation model of ice force action in time was developed on the basis of the mathematical model of failure process at contact surface and statistical data about ice regime parameters in situ.

The proposed model gives an opportunity to receive the ice force as a stochastic process or another words with main force characteristics. In the case of application of a simplified model of ice failure process one can estimate the ice force distribution, number of cycles and other parameters as stochastic values.

The given information may be expressed as histograms of ice parameters distribution or as time curves of stochastic values with their *probability characteristics.

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ON THE QUESTION OF THE PHYSICAL PROPERTIES OF SEA ICE

Spatial orientation of crystallin structures of sea ice characterized by the degree of order of principal optic axis in its azimuth position due to the effect of currents are widely distributed both in fast and pack ice in polar regions. Laboratory studies and full-scale research of sea ice show that due to permanent flows under the ice the crystals of fibrous structures aspire to fill a position at which their principal optic axis becomes parallel to the direction of flow. As a result, the spatially ordered azimuth orientation of crystals that stipulates anisotropy of physical proportion of sea ice is created in ice fields.

The mechanical characteristics of sea ice samples, obtained experimentally by the technique recommended by the Ice Committee of International Association for Hydraulic Research, have been analyzed. A relationship has been found between the ice strength at uniaxial compression and the direction of load application (structural anisotropy). The strength of ice with fibrous structure changed within 30% of the maximum value corresponding to the direction of load application along the principal optic axis. An analogous dependence has been obtained also for the rate of distribution of longitudinal waves in ice samples.

The experimental studies on electric characteristics of sea ice in the microwave range have also revealed a considerable anisotropy of specific attenuation of electromagnetic waves and the index of refraction for ice of different types and age.

The changes in these values depending on the turning angle of electromagnetic field intensity stress vector relative to the dominating direction of principal optic axis of oriented crystals are rather considerable: they amount to 70% and 10% of maximum value respectively.

Thus, a comparative analysis of structure, physico-mechanical and electrical characteristics obtained for the same ice samples allowed one to be convinced in not only close interrelation between the above parameters, but also to give its quantitative estimation. The results obtained gave the grounds to believe that anisotropy of physical properties is to be taken into account when solving applied problems, particular, when improving the methods for numerical estimation of interaction forces between sea ice cover and engineering structures.

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MODELLING THE CONSTITUTIVE PROPERTIES OF SEA ICE SINGLE CRYSTALS

Little is known about the importance of intracrystalline deformational processes as compared to intercrystalline processes for determining the mechanical properties of polycrystalline ice. This is particularly true for sea ice, since the presence of brine may have a significant effect on both of these processes. This effects are not yet well understood.

In order to obtain a better understanding of the role of intracrystalline deformation processes, a study involving both analytical modelling and laboratory testing was undertaken. First the deformation of single nonsaline ice crystals was described in terms of dislocation strains on a discrete set of dislocation systems involving the basal, prism, and pyramidal planes. Crack damage effects were not initially included, since only low-to-intermediate strain rates were considered. Calculated results showed realistic material behavior for creep strains, delayed elastic strains, stress response to prescribed strain rates, and stress relaxation. For sea ice single crystals an additional deformation mechanism due to the platelet substructure of sea ice was added to those already determined for nonsaline ice. This additional effect was represented as a coupled slip process on the basal plane due to the viscous interplatelet slip in the brine layers separating the platelets and the dislocation strains occurring in the ice inclusions which connect many of the platelets. Calculated results showed that this additional mechanism can potentially have a significant effect on the material properties.

A series of constant strain rate tests on single sea ice crystals and nonsaline single crystals were completed. These tests provided a preliminary comparison of the properties of these two single crystal materials. The results showed that under constant compressive strain rates, the peak stress reached with the nonsaline ice was almost an order of magnitude higher than for the sea ice. The steady flow stress was roughly three times as large. These differences in the

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properties of saline and nonsaline single crystals appear to be larger than for polycrystalline ice, thereby suggesting that intracrystalline effects may not be the predominant processes which determine the properties of polycrystalline ice, either nonsaline or saline.

Current work involves more detailed testing of single crystals over a temperature range of -10°C to -40°C. These tests should provide a better understanding of the deformation mechanisms which determine the properties of sea ice crystals. Work is also continuing on the analytical modeling, where more comprehensive descriptions of the dislocation dynamics are being studied.

D.M. Cole

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SOME RECENT DEVELOPMENTS IN EXPERIMENTAL ICE MECHANICS AT CRREL

This talk focuses on two general aspects of experimental ice mechanics that are currently under investigation at the U.S. Army Cold Regions Research and Engineering Laboratory. The first is the response of various types of ice to fully reversed (i.e. alternating tension-compression) uniaxial stresses. The unique apparatus developed to grip the specimens rigidly in the testing machine is described, experimental results are presented, and the influence of stress, frequency, temperature, and microstructure on the internal friction, and inelastic strain are examined from a micromechanical viewpoint.

Additionally, a newly developed system for performing pulse-echo experiments on ice at frequencies near 20kHz is presented, along with results obtained on large ice single crystals. These results are discussed in terms of the proton rearrangement mechanism of internal friction.

M.D. Coon

The BDM Corporation

THE MECHANICS OF PRESSURE RIDGE BUILDING
FROM A WIDE VISCOELASTIC PLATE

Recent measurements of sea ice stress associated with ridge building and time dependent analysis of lead ice indicate that a wide plate analysis of young ice may help determine ridge building forces. These forces are important in large-scale ice dynamics in that they will control the large-scale stress. Therefore, they are also of importance in determining the loads on structure if the concept of limited driving force is adopted.

In this paper, the ice in a lead is treated as a linear viscoelastic material and the appropriate bending equations for a uniform thickness plate loaded on two edges are developed. These time-dependent differential equations are solved to determine the failure load of the plate for various rates of loading. The results will depend on elastic or viscous properties of the young lead ice. The appropriate properties are those for a plain strain analysis and the appropriate properties emerge from the analysis. Temperature variation through the thickness of the plate is considered in relation to the mechanical properties. In situ and laboratory experiments to determine that appropriate mechanical properties are discussed.

The failure loads for lead ice are used to examine possible formulations for large-scale sea ice strength. This strength would be appropriate for use in geophysical scale ice dynamics modelling. The results are also used to interpret the maximum time dependent forces which can be transmitted through an ice cover. The same stresses are available to load offshore structures in Arctic waters. Where appropriate, measured sea ice stresses and mechanical properties are used or compared with the calculated values presented in this paper.

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PREDICTION OF THE MECHANICAL PROPERTIES OF UNDEFORMED FIRST-YEAR SEA ICE DURING THE GROWTH SEASON

A model has been developed to predict the composite mechanical properties of a growing first-year sea ice sheet. The model assumes a linear temperature profile and considers the energy balance at the ice surface, initial salt entrapment, brine drainage, and suction. Estimated salinity profiles are in good agreement with natural profiles. Although the temperature and salinity profiles depend on the time of year when ice growth is initiated, the resulting brine volume and mechanical properties are unique functions of the ice thickness. These results provide justification for parametrizing the mechanical behavior of pack ice on the basis of an ice thickness distribution.

The temperature and brine volume profiles are utilized to calculate ice strength and elastic modulus profiles which characterize the composite mechanical properties of the ice sheet. Significant differences are found between the ice sheet properties calculated using the composite plate theory developed by Assur, and the properties calculated from uniform plate theory using average ice properties. This is particularly true for thin, young sea ice sheets.

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SEA ICE MECHANICS IN THE CONTEXT OF U.S. ARCTIC MARINE BASIC RESEARCH

The interests and efforts of federal agencies in Arctic marine basic research are reviewed. Within this context current and future activities related to air-ice-ocean interaction are discussed. Two sea ice-related initiatives are described in detail: lead dynamics and sea ice mechanics.

Lead dynamics focuses on local oceanic and atmospheric heat flux processes, new ice formation, and regional fracture distribution in response to forcing. Sea ice mechanics addresses constitutive relations and fracture mechanics in the scale range from a few centimeters to a few kilometers with scale interrelationships a primary issue. Both modelling and field observations are outlined.

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FRACTURE BEHAVIOR AND SIZE EFFECT

This workshop presentation will focus on the following topics:

- the laboratory scale fracture behavior of sea ice;
- the effects of microstructure, temperature, salinity, and porosity on the fracture behavior of sea ice;
- the nature of crack nucleation, initiation, and propagation in sea ice;
- specimen size effects: the determination of fracture behavior of sea ice at the structural scales - with the associated temperature and salinity gradients - from laboratory scale behavior.

At the laboratory scale, the issue of notch sensitivity and brittleness of the test failure is used to forecast the necessary specimen size for a material property initiation toughness; a methodology has been developed suitable for all test geometries. The scatter in the fracture toughness values reported in the literature is partially accounted for by examining the requisite notch acuity or crack tip sharpness. The mechanics and physics of crack nucleation and propagation in sea ice is closely related to the topic of crack growth stability. Closely related to this subject are concerns such s: under what conditions (if at all) does a crack in ice remain atomically sharp, and under what conditions will blunting take place? If crack-tip blunting occurs, or if blunting does not occur but fracture reinitiation requires a larger energy release rate, what are the underlying mechanisms, and what are the most applicable concepts of fracture mechanics? Information related to the above issues are of fundamental importance to applications involving the fracture of ice and the fracture of quasi-brittle materials in general.

An exact quantification of the fracture process in sea ice is made difficult by the coupled interaction of three major factors: polycrystallinity, high

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temperature brittleness, and rate effects. For instance, in terms of tensile fracture and fracture testing, there appear to be two options available:

- upgrade the size of all specimen geometries until the notch sensitivity and brittleness is such as to ensure the applicability of linear elastic fracture mechanics;
- adopt the principles of nonlinear fracture mechanisms and concentrate on the associated toughness parameters, testing sub-size specimens.

The first option will simply not be viable for certain types of ice and certain specimen geometries unless one is to plan large-scale tests. Concerning the second option, size effects on several fracture parameters and the use of nonlinear fracture mechanics has already received considerable attention for materials such as concrete and rock; much work is needed on this topic for sea ice.

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A SHIP IN AN ICE COVER UNDER COMPRESSION

Results and preliminary theoretical analysis of model tests conducted to study a ship in compressive ice are presented. The investigation forms a part of a joint research project between Helsinki University of Technology (HUT)/Laboratory of Naval Architecture and Marine Engineering and the USSR Academy of Science/Institute for Problems in Mechanics.

The tests are carried out in the HUT ice model basin. The total number of tests is 54 with two ice thickness and including tests in level ice, channel, compressive level ice and compressive channel. Towing force, speed and maximal compressive force against port-side are recorded. The resistance in the compressive channel can be twice as large as resistance in level ice at low speed.

Experimental results analysis led to mechanical model of a vertical wall and ice platen interaction. In a steady regime the interaction zone is divided into two parts: the region of direct mechanical contact of the wall and ice platen, and the region where the contact takes place only through fracture products. Introducing governing equations for intermediate-layer material it is derived relation for ice pressure on the wall (ship hull) in dependence on compression level and wall motion speed. The results of calculations are in consent with experimental data.

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DEFORMATION AND FRACTURE OF ICE

Ice deformation and fracture is considered as a set of mutually connected and interdependent processes in various scales taking into account ice structure, strain rate, and temperature influence. There are discussed mainly results of the investigations of 1) deformation and acoustic emission observation for microcracking and 2) fracture in the presence of cracks or cracklike defects.

There are suggested some hierarchical structural models describing interconnection 1) macrodeformation and microfracture parameters and 2) macrofracture toughness (and macro hummok resistance) with deformation characteristics.

Temperature-strain rate dependences for ice deformation and fracture parameters are discussed.

There are demonstrated some ways for using established regularities in the solution of applied problems including a problem of ice and ice cover interaction with structures and icebreakers, and a problem of engineering glaciology.

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MATHEMATICAL MODELLING OF LARGE-SCALE FLOATING ICE MOTION

(Abstract not available)

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BEARING CAPACITY OF ICE COVERS SUBJECTED TO STATIC AND OSCILLATORY LOADS

Early empirical methods for the determination of the bearing capacity of floating ice plates that are subjected to static or quasi-static loads of short duration.

Bearing capacity analyses that utilize the elastic theory of plates. Analytical failure criteria. Discussion of the governing differential equations for nonhomogeneous plates. Effect of the nonhomogeneity of the distribution of bending stresses, and its effect on the use of the common stress failure criterion. Simplification of the analytical results and their comparison with corresponding expressions of the empirical methods.

Presentation and discussion of test results on bearing capacity. Upper and lower bound criteria for engineering applications. Comparison of analytical results with laboratory and field test data. Comments to the determination of E_* and a_f, the failure stress.

Carrying capacity of ice covers subjected to loads of long duration. Review of analytical attempts. Field and lab findings. Drop of carrying capacity with progressing time. Discussion of needed analyses. Choice of proper constitutive relations. Failure criteria.

Bearing capacity of ice covers subjected to oscillatory loads. Ice cover fatigue. Description of recent tests and presentation of recent test results. Planned test program for ice cover fatigue and recovery.

Conclusions and recommendations.

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SIMULATION OF ICE LOADS ON SHIP HULLS AND OFFSHORE STRUCTURES

1. The interaction of the ship's hull and the ice is considered as a random process with a large number of random values with complex correlation relationships. To construct a joint function of the distribution of these values and to obtain thus a function of the ice load distribution appears to be actually impossible. The modelling of the interaction can be made by means of the Monte Carlo method.

2. The modelling of the interaction between the ship's hull and the offshore structure and the ice is carried out according to the standard scheme:

Random ice   A model of interaction   Random ice
conditions   (deterministic)   loads

As a result of the modelling the distribution functions of load parameters are determined.

The realization of this scheme requires the following integral blocks:

- the data base on the ice situation en route of the ship's motion or at the site of the structure to be established;
- realization of the interaction conditions;
- random physical-mechanical ice properties;
- calculation of the ice load realization;
- accumulation of ice load realizations and procession of the distribution functions.

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3. The following major problems can be solved by means of the statistical modelling of random ice loads:

- to determine the probability of damaging or exceeding the prescribed level of the loads from the results of modelling (risk model);
- to model field trials of the objects;
- to model the non-uniformity of the loads with large contact zones.

4. To fulfil these goals requires additional models, which are not the models of the interaction between the ship or structures with the ice.

- a model of the construction failure, for the ships usually a maximum permissible load, determined by a rigid-plastic model is assumed;
- a model of the measuring scheme, which includes a construction model with the locations of the sensors and data recording; in most cases the construction model with the scheme of the sensor location can be represented by a matrix of influence coefficients, and the realization of the external loads is reduced to the system of concentrated forces;
- a model of a random form of the edge, which can be obtained from the "white noise" by means of the forming filters.

The fulfillment of these objectives will enable one to estimate the representativeness of the experiments, to interpret the data of field trials in the designing of new constructions, to model the consequences of the ships and "off-shore structures" maintenance under ice conditions.

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STUDY OF ICE ACTION ON OFFSHORE STRUCTURES

The development of sea transport ways and exploitation of shelf zone of ice covered seas caused the complex problem of design and construction of offshore structures including ice-resistant platforms. One of the main problems is estimation of ice forces on offshore structures. These problems have been studied more than twenty years long by divisions of Far Eastern Polytechnic Institute according to a special program. The main items of this investigations are:

- studying of sea ice properties as material;
- working out and basis of yield criteria for sea ice;
- working out of express methods for definition of yield characteristics of sea ice;
- theoretical and experimental study of drifting ice cover-structure interaction;
- working out of mathematical models ice cover failure processes at structure contact;
- working out of mathematical models of dynamic ice-structure interaction;
- working out of methods of physical modelling of ice-structure interaction and technical means for this purposes;
- working out of analysis method for ice force regime definition during ice cover-structure interaction;
- hummock action of offshore structures;
- working out of means and devices for ice cover destruction and decreasing of ice force.

The new types of ice-resistant structures were proposed on the basis of investigations and analysis methods of ice forces which are used in designs for exploration of carbon resources on the Sakhalin shelf.

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NUMERICAL SIMULATION OF THE DRIFT OF A VARIABLE THICKNESS
ICE COVER IN THE ARCTIC OCEAN

Sea ice velocity is determined by balance of forces, such as wind and water stresses; Coriolis force; currents and tides, caused by the sea level inclination and forces of the internal interaction of the ice flows with each other and with the shores. By the term "drift velocity" we understand in this case he velocity of the center of masses of the ensemble of flows, distributed in the element, linear dimensions of which are equal to the grid step.

The air and water stresses can be determined, if the integral effect of the boundary layers, which are forming above and under the ice, is known.

The maximal hardships at present time by the numerical simulation of the ice drift are caused by the form of the internal interaction force in the ice cover. The real ice cover is a complicated formation, containing features of elastic, viscous, and plastic deformations.

The notion of the ice cover as a viscous incompressible film is a rather simple approach. The combination of the momentum balance equation with the condition of incompressibility allows us to write the equation for the ice pressure of the Poisson's type.

The introduction of a parameter-threshold of compactness is an essential peculiarity of the model. If the meaning of the compactness is lower than this threshold, the ice flows don't interact and the ice pressure in this point equals zero. The meaning of the speed divergence by the compactness being lower than the interaction threshold differs from zero.

The governing equations of the model include also equations of evolution of the ice cover compactness and thickness. They can be written in the form for the

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general compactness and the mean ice thickness and in the form for the partial compactnesses and thicknesses for the different ice categories.

The surface atmospheric pressure fields, initial fields of compactness and thickness of the ice are used as initial data for the calculations.

Test of the model was done for an area of 3000 x 2800 km approximating the Arctic Ocean and the Arctic shelf seas. Grid step was equal to 200 km, time step was equal to 600 s.

The charts of the drift of the automatical buoys were used as a main test material. The drift of the buoys was averaged for the period of 5, 10, 15 days and for the month.

The calculation of the drift direction came true in 94% of the cases. The mean ratio of calculated and real moduluses of the drift speed was equal to 0.74.

The ice thickness redistribution for different ice thickness categories was simulated for the section of the Arctic ocean the Chukchi sea for the three and five categories, respectively.

The fulfilled calculations allow us to tell, that this model, in spite of its relative simplicity, rather well reflects the main feature of the ice drift in the Arctic ocean, gives the opportunity to calculate ice thickness redistribution for the month period even with maximal detalization of the ice cover by thickness categories.

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PROBLEMS RELATED TO THE STATIC STRENGTH OF AN ICE COVER

The paper is of a review character and concerns to ice cover static analysis problem. Ice cover is considered as a plate on elastic foundation. The paper includes two parts. The first one deals with analysis theoretical problem of the plates on elastic foundation. The second part deals with some special ice cover strength problems related to a great extent, to experimental result analysis.

In the ice cover design infinite plate problem solution including the case of load distribution along circle surfaces, is of great importance. In many cases the solutions are obtained in closed form in terms of cylindrical and contiguous function.

In the main part of the paper the problems of finite layers of constant thickness and infinite plates with openings are examined. There is discussed the interrelation between compensated loads method and Treffts-Friderichs variational method, as well as boundary integral equation application. The problem of cracked plate subjected to a load, distributed along circular surface is discussed. That arises from studying the process of infinite plate failure.

The problems of the plates with variable thickness on elastic foundations are considered in detail. There are obtained the solutions of circular plates of linearly varying thickness, subjected to symmetric and antisymmetric loading and complete solution of the similar problem when the thickness varies with the radius according to the law of 4/3 power. Analysis the plate areas, adjoining to the supports of the structures, it is possible to utilize approximate solutions considering reactive force, exerted by liquid, as constant. The problems of circular and annular plates with different laws of variable thickness are investigated. All above mentioned solutions are obtained in closed form in the terms of different special functions. In all cases, Green's functions are determined. Considering the influence of elastic foundation, there is utilized

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iteration method. Briefly the rectangular plates with variable thickness are analyzed.

The second part of the paper analyzes the results of experiments on ice crust strength. These crusts are formed as a result of ice freezing in polynia-bath. Major differences between key and plate strength problems are discussed here.

Short remarks, concerning the possible application of above mentioned problems in analysis of artificial ice cover strength increase and the reverse problem of its destruction are given here.

Model problem of plate and beam with upper reinforcement are considered in this aspect.

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INVESTIGATION OF ICE AND ICE CLATHRATE CHARACTERISTICS

Gas hydrates are icelike crystal compounds formed from gases and water at certain thermodynamic conditions and resembling snow or firm ice. The crystal lattice of these compounds consists of water molecules which are hydrogen bonded to each other. Gas molecules are included into lattice cavities and interact with it under the influence of Van der Waals forces. in the absence of gas molecules the lattice is thermodynamically metastable in contrast to a crystal lattice of ice.

Similarity of ice and gas hydrates structures allows to compare their physical and-mechanical properties including mechanical and adhesive ones.

Hydrate adhesion is of great practical interest. Hydrate formation on pipe walls in the systems of production and transport of natural gas reduces the pipeline capacity up to a complete stoppage of gas supply. To develop methods preventing hydrate formation one must know the adhesion strength of a hydrate-substrate bond.

In the report the ice and hydrate adhesion strength was determined with the help of the experimental set made in two modifications. In the first one the external force required for breaking the adhesion bond is induced by electric current through an inductance coil with a core being rigidly linked to a substrate. In the second one the breaking off force was produced by the drop of gas pressure on the piston connected with a substrate.

Hydrates of a natural gas, freon-12, and tetrahydrofuran and ice obtained from the distilled water were studied. Samples made of steel, duralumin, and polytetrafluoroethylene were use as a substrate. A surface finish class and interfacial angle were determined for each sample.

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Experimental data show that the adhesion strength of ice in the temperature range 253-373 K grows with temperature decreasing for hydrophilic surfaces (steel, duralumin) and practically does not change for hydrophobic ones (polytetrafluoroethylene). The adhesion strength of ice for steel and duralumin is much higher than that for polytetrafluoroethylene. The ice-polytetrafluoroenthylence system in the temperature range considered is characterized by the adhesion type of breaking, while for the ice-steel system at certain temperature the transition from the adhesion to the cohesion type of breaking is observed.

Experiments showed that temperature dependence of the hydrate adhesion strength is similar to that of ice, i.e. the adhesion strength grows with temperature decrease for hydrophilic surfaces and practically does not change for hydrophobic ones. The adhesion strength of hydrates considered is almost independent of a gas molecule type.

The adhesion strength of hydrates was evaluated on the basis of the theory of molecular interaction and Griffith theory of fracture.

special experiments were carried out to compare acoustical properties of porous media saturated with ice and gas hydrates. Three types of samples were tested: sands of particle diameter in the range 0,15-0, 30x10^{3}m and in the range of 1,5-2, 0x10^{3}m; silicagel of average pore diameter 85,5A and particle diameter 1,0-2, 0x10^{3}m. The results reveal the clear influence of water content and temperature on velocity and damping of acoustic waves propagating through the samples. The temperature difference between water-ice phase transition and reaction of clathrate formation is about 10K. Acoustic wave velocity of sand saturated with gas clathrate is 3-4 times of that saturated with gas and water. The effect is intensified with increasing of water saturation.

The results of experiments with silicagel samples were quite different. The increase of velocity was not more than 30% though the temperature was lowered down to 262K. It is explained by the presence of strongly bonded water in very small pores.

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A MODEL OF DRIFT ICE

The ice cover swimming on the horizontal surface of ocean is considered. The ice cover consists of ice-flows with various forms, geometrical scales and safety properties. The typical horizontal scale of ice-flow is more less than horizontal scale of investigating phenomenon. It is supposed that ice flows on the surface of ocean is even and its relative velocities are small, so ice cover may be considered as continuous media with viscous-elastic-plastic properties. The plastic properties are bound up with irreversible changes of ice cover that are conditioned by destruction of ice-flows.

Two forms of ice-flow interaction may be considered before hummocking: 1) collisions and 2) mutual pressing and friction in places of contacts. The first kind of interaction is realized when each ice-flow may move in its neighborhood without collision with other flows. The second kind of interactions have place when ice flows can't move without change of disposition of other ice-flows. In the first case we say that ice cover is in a diffuse state and in the second case in a compact state. The change from the first to second state is realized by compression deformations.

It is supposed that the compactness A1 is being when diffuse ice cover with compactness A (smaller than A1) changes in compact state. Hummocking may be realized if A=A2 (greater than A1).

In the presentation the break solutions are investigated. The problems about collisions of two ice cover field with various compactnesses with each other and ice cover field with rigid walls are considered. The pressure of ice cover on the wall is defined in dependence on drift velocity and compactness.

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THE MATHEMATICAL MODELLING OF ICE INTERACTION WITH VERTICAL PILES

This paper deals with developing a simulation of deformation and fracture of the ice cover around the structure when aspect ratio is high, i.e. a width of the structure is much larger than the ice thickness, so the plane stress condition can be used to investigate the stress distribution in an ice around the structure.

The ice is simulated as an elastic-brittle material and the modified Coulomb-Mohr theory is used to describe crushing of ice field. This scheme allows to describe both the fracture of ice by tear and shear. The model of ice field described above was used in the finite-difference program SHELFpM which was developed during 1985-1988 at LPI. The main advantage of SHELF-M over the existing FEM programs (MARC, ADINA, MGEEMO) used by Western specialists to study the ice-structure interaction is in the dynamic approach that allows to simulate the fast propagation of the cracks in an ice sheet. During the last years the program has been used in about 400 numerical experiments. The computer experiments have been performed by EC-1060 and IBM PC AT. The ice force has bee calculated by displacement loading. The force-time curve and the fractured zone development and epures of normal and shear stresses acting onto the structure has been received in each of the numerical experiments. It has been shown that the ice force amplitude depends essentially on the ice strength properties (the angle of the internal friction and the St/Sc ratio).

In these investigations the influence of the following factors has been studied:

- Structure cross section. The circular, octagonal, square and rectangular structures have been studied.

- Boundary conditions. The two kinds of boundary conditions at the ice-structure contact have been simulated - the stiff boundary (the structure

is frozen in the ice sheet) and the free boundary (the friction between the ice and the structure is absent).

- Increasing of the ice thickness near the structure (ice cone shape and size). Three different ice cones have been studied: $h=h0$ (ice cone is absent), $h = h0(1+1/r)$ (shallow ice cone), $h = h0(1=1/r^3)$ (steep ice cone).

- Adfreezing ice strength. The adfreezing ice strength has been described by Coulomb-Mohr equation too. So the tear and shear adfreezing strength of ice was taken into account.

The ice forces acting onto the monocone structures frozen - in to an ice sheet has been studied too.

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INSTABILITY AND SELF-ORGANIZATION OF ICE SHEETS

Ice-creep instability is a well-known example of ice-sheet instability, and there are a variety of other ice properties that lead to instability. But ice sheets interact with their environment - the atmosphere, ocean and lithosphere - and it is the interaction that leads to a new variety of instabilities in both the ice sheets and environment. The entire dynamic systems coupling and comprising the ice sheets with the atmosphere or/and ocean or/and lithosphere are considered to study mechanisms of instability.

For an ice sheet interacting with the atmosphere, a "cubic" curve and a "cusp" surface of ice-sheet equilibria is found in perfect-plasticity shallow-ice approximation. The instability puts limits on the ice-sheet dimension. It is shown that an advanced ice sheet can be stabilized only at the very large dimension. Polar ice sheets (e.g. the Antarctic Ice Sheet and former arctic Ice Sheets) aren't stabilized until they reach the ocean and are transformed into either marine ice sheets or marine ice sheet/ice shelf systems (marine ice systems). But interaction with the ocean does not stabilize the advance but causes a new- marine mechanism of instability which leads to a fast collapse of marine ice sheets and marine ice systems.

A marine ice system is a single dynamic system while its members - grounded ice sheets, floating ice shelves and transitional zones - are different in terms of dynamics. The dynamics of grounded ice sheets is controlled by shear stresses while longitudinal stresses are small; on the contrary, the dynamics of floating ice shelves is controlled by longitudinal stresses while shear stresses are small; the ice sheets and ice shelves are connected by transitional zones (ice streams) where both the shear and longitudinal stresses are comparable. The dynamic differences result in morphologic ones: longitudinal profile of the ice sheets is convex; it becomes concave within the transitional zones (the inflection line

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may be adopted as a conventional boundary between the ice sheets and transitional zones); the ice shelves are nearly flat.

The mechanics of the members of marine ice systems as a whole is considered in perfect-plasticity shallow-ice approximation. The transitional zones are treated as "weak."

However, instability of ice sheets is not only "destructive" but it may be "creative," if the instability results in synergetic effects and leads to self-organization of regular spatial structures within and ice sheets. For example, the instability caused by the erosional interaction of ice sheets with their beds gives a natural mechanism for self-organization of ice streams within ice sheets and large-scale linear forms (coastal fjords and submarine troughs) within their beds.

The model of eroding ice sheet/eroded beds is considered in viscous shallow-ice approximation.

Glacial instabilities discussed here is a convenient tool to explain the Cenozoic ice-sheet variations and global-climate changes.

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ICE ISLAND STRUCTURES FOR EXPLORATION DRILLING

Discovering commercial oil and gas reserves on the Arctic continental shelf calls for the development of offshore drilling platforms and equipment designed for operation in the hostile environment with short ice-free periods. A considerable amount of predicted hydrocarbon reserves in the Arctic seas is attributed to shallow water areas where the use of floating drilling units and fixed platforms is most difficult due to the deep draft during transportation. Under this circumstance the most practicable way is to use ice island structures, particularly at an early stage of exploration. They are constructed using artificial ice generated by either volume or layer by layer seawater freezing on the prepared foundation or using various combinations of artificial and natural ice with foreign additives (fillers). The selection of the construction procedure is dependent on the site of construction, temperature conditions in the region, and the availability of particular types of ice.

The world experience in construction and operation of artificial ice islands shows that a number of important problems exist. These are: ensuring the rate of freezing required for the successful construction and operation of artificial ice islands; generating large amounts of high-strength monolithic ice for the structure body with certain physical and mechanical properties and ensuring its resistance to all the external loads so that the artificial island could operate as a foundation for exploration drilling. The VNIPImorneftegaz, Moscow, has conducted large-scale experiments on the fast ice of the Kara Sea with a view to define practical ways of generating large ice monoliths (up to 3 million m^3) by seawater freezing (salinity of 34-35), which is the principal and most complicated problem. The other objective of the experiments was to test existing theories and to finalize the development of procedure of ice island construction. The construction was performed by sprinkling seawater according to a pre-set cell

layout with the brine flowing down inclined side surface of the cells. The procedure was tested under various conditions, namely at various angles of nozzle inclination to the horizontal, with various number of nozzles and their outlet diameters and with various values of water head, air temperature, and wind speed and direction. Ice-generated procedure was tested alongside with studying physical and mechanical properties and thermodynamic behavior of generated ice mass.

The results of field experiments and theoretical investigations helped to produce guidelines for ice island construction and to define problems requiring further investigations.

D.E. Nevel

Conoco Inc.

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PROBABILISTIC ICE FORCES

This presentation presents a method for predicting probabilistic ice forces on offshore structures. It discusses the development of probabilistic distributions from environmental data, and the formulas which are used to compute the ice forces. For one type of ice feature, many forces are calculated and a probability is assigned to each force to obtain the probability distribution. A method is developed for combining ice force distributions for more than one type of ice feature.

The return period of a force is defined and the selection of its design value is discussed. The probability of exceeding the force in the time period, such as the life of the structure, is considered. Future developments are discussed with emphasis on obtained better ice data.

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MODELLING THE BRITTLE COMPRESSIVE FAILURE OF ICE:
POSSIBILITIES AND IMPLICATIONS

When ice is loaded in compression, a variety of behaviors may occur. At very low rates, deformation is without cracking and appears dominated by recrystallization. As the loading rate is increased, the ice exhibits some cracking, and the stress-strain curve shows a clear peak. This peak apparently arises from the cracking activity. After the peak, the stress decreases to a plateau value an in this portion of the stress-strain curve, deformation is again due to recrystallization. As the strain rate is increased further, the sample will fail catastrophically as a result of cracking activity. Quite how the failure occurs is not clear, but three mechanisms of brittle compressive failure have traditionally been identified in the rock mechanic literature: axial splitting, shear faulting, and cataclasis.

Recent work in the ice literature has concentrated on the Wing Crack model put forward by Ashby and Hallan (1986), and has attempted to describe the failure process as being due to stable propagation of wing cracks. However, at least two other possibilities must be considered. One is that wing crack may indeed cause failure, but by an unstable crack propagation mechanism. The second is that rather than wing cracks causing the failure, the initiation of new cracks into the aggregate may give rise to a catastrophic reduction in stress. Also, models to date have failed to identify clearly the actual mechanism by which instability occurs.

This paper will present three possible models for brittle compressive failure in ice. The limitations of each of the three models will be discussed, along with the implications of their respective functionality. Given then the behavior being modelled is brittle, some degrees of scatter is to be expected in any experimental results, and the nature of this scatter will be considered.

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Those results which are available in the literature will be discussed in the light of their models, along with more results obtained by the author. It will be seen that none of the existing models describe the available data completely, at least in part because insufficient information on the failure of each sample (i.e. whether splitting, shear faulting, or cataclasis occurred) is available. Directions in which future work might prove fruitful will be indicated.

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SEA ICE DYNAMIC MODELS

A sea ice dynamics model based on an elastic plastic constitutive law is reviewed. Ice condition is described by the thickness distribution. Strength is estimated by balancing the rate of work done by stress during deformation with the power dissipated by the small scale energy sinks: gravitational potential energy increases, frictional sliding, and shearing. The specific choices of yield surface, flow rule, and mechanical redistribution are justified by reference to the literature. The model is designed to describe and forecast ice behavior over periods of about a week. Changes in ice velocity, deformation, stress, and ice condition are described. These variables, although averaged over tens of kilometers, provide valuable information to designers and operators of offshore structures since ice strength limits the force that can be applied to a structure.

Mathematical characteristics are examined to help understand the large-scale lead patterns observed throughout the Arctic, especially where ice is forced through straits and other restrictions. The metals and soil mechanics literature contains numerous discussions of plasticity models and the importance of characteristic directions or slip lines for describing discontinuities in the deformation field. Polar literature now also contains several similar references. The quasi-steady ice dynamics model is hyperbolic, parabolic, or elliptic depending on the yield surface shape and stress state. When hyperbolic, two real characteristic directions exist, across which traction can be discontinuous. Velocity characteristics coincide with stress characteristics if an associative flow rule is used, but may be independent if a non-associative flow rule is used. The present work explores more thoroughly the model behavior associated with the characteristics in an attempt to learn if they can really be expected to describe the observed lead patterns. Of interest are directions along which leads form and the deformation of existing leads. The latter topic is of special interest when pairs of rectilinear leads co-exist.

The different possible relationships between observed lead patterns and characteristics are examined. Several different explanations are evaluated: (i) leads form and deform along stress characteristics; (ii) leads form stress characteristics and deform along velocity characteristics; (iii) leads form along stress characteristics and deform along directions of maximum opening; and (iv) intersecting leads form sequentially, rather than in pairs along the two characteristic directions. The possibility that lead patterns are not related to mathematical characteristics is also considered. While our present understanding suggests that (iii) provides the most likely explanation, more data are needed to substantiate the conclusion.

Several special cases are considered: flow around an obstruction, arching across a strait, and shearing along a coastline. In the future, data available from satellite imagery will be most useful. Sequential images must be analyzed to determine when leads formed and how they deformed.

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ICEBERG IMPACT PRESSURE AND FORCE DESIGN CRITERIA FOR FIXED PLATFORMS

Where present in significant numbers, icebergs dominate the design of fixed offshore platforms. Such is the case on the Grand Banks of Newfoundland where a large gravity based platform has been considered for production at the Hibernia Oil Field.

A substantial amount of information is available about the physical properties of icebergs. Less information exists about the pressure and forces that may result from their collisions with offshore platforms. Very little can be found as to how to apply the iceberg impact pressures and forces for local and global design of the platforms.

The author presents of comprehensive review of the procedures for iceberg loading calculation and application. He also addresses: (a) the key differences between icebergs and sea ice; (b) the iceberg data and impact load algorithms needed to establish design criteria; and (c) possibilities for further reduction of the present conservatism in the iceberg loading criteria.

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CRACK PROPAGATION IN AN ICE COVER UNDER THE ACTION
OF A MOVING NORMAL LOAD

The problem of dynamical crack propagation in ice cover (which is assumed to be a homogeneous elastic plate) differs from the classical problems of fracture mechanics in certain features. First, it is nonlocality, i.e. the action of forces bending the ice cover is transferred to its distant areas not only by the bending waves moving along the plate, but also by the waves in water. This fact considerably influences on the mathematical formulation of the problem: differential equations of dynamical bending of a plate, contacting with water, are transformed to a convolution-type equation (which makes its solution more difficult). That is why in this paper we shall first consider the fundamental problem of a normal moving force. Incidentally, solving this problem helps to find out feasible one of simplifications in the descriptions of plate-water interaction.

Secondly, the problem under consideration is characterized by critical velocity (i.e. velocity of movement of normal force and crack propagation) which is very little as compared to corresponding critical velocity of crack in elastic medium (usually it is Rayleigh's waves velocity). The moving load induces waves carrying energy away "to infinity" if the velocity is greater than the critical one. In this case (in contrast to under-critical range) only a part of energy is spent on fracture (flowing down a crack tip), another part is radiated by the waves mentioned above. The power of this radiation is to be included in correlation between load intensity, velocity, and location of a stack with respect to the load.

All these aspects of the problem are considered.

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MECHANICAL PROPERTIES OF SEA ICE: LABORATORY EXPERIMENTS

Models that are being developed to predict the behavior of sea ice during ice-ice and ice-structure interaction require information on the mechanical properties of the ice. The level of detail necessary in the constitutive description of the behavior of the ice still remains a question. In other words, do we (or can we) incorporate the models developed to describe the micromechanical processes observed in 10-cm laboratory test specimens directly into the larger-scale models designed to predict the failure of ice sheets? Probably not, since this level of detail would result in interaction models that are too cumbersome to be useful, practically. We still need to understand the small-scale processes, however, in order to define the variables of primary importance in controlling the behavior of the ice.

This presentation will focus on laboratory work that has been done to determine the small-scale material properties of sea ice as a function of ice structure, temperature, loading rate, and state of loading. Techniques for performing uniaxial compression and tension and confined compression tests on 10.2-cm-diameter, 25.4-cm-long cylindrical test specimens will be described along with the combined results from these various test programs. I will also describe test facilities that are being established to permit laboratory testing of 1-m-scale ice blocks in compression and bending. These blocks will be loaded _in situ_ and, hence, will have a temperature gradient representative of ice in the field. We plan to model the loading behavior of these blocks using data from small-scale material property tests. This effort will serve as an intermediate step towards relating the insight we have gained from the material property tests to the field scale interaction events.

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THE ICE RESEARCH PROGRAMS AND EXPERIMENTAL FACILITIES
OF THE KRYLOV SHIP RESEARCH INSTITUTE

The experience that has been accumulated so far in the solution of practical ice technic problems shows clearly that the main role in this still belongs to experimental methods of research. This is largely accounted for by the fact, that ice, particularly sea ice, is still among the less studied media and may be characterized as a material widely varying its physical properties with variation of numerous external factors. It presents considerable difficulties in building up theoretical models which would describe the diversity of ice reactions to external loadings.

On the other hand, the possibilities of full-scale experiments in ice conditions are strongly limited by heavy expenses to prepare and conduct them, rather poor informativity of the results obtained due to a random character of ice situation in the test area, considerable technical and ecological risk, especially in cases when experimental samples of transportation means, offshore floating or stationary structures are investigated.

With the advent of new types of physical laboratories - ice model basins (more than 20 in the world now), of which the ice basin of the Arctic and Antarctic Institute, USSR, was the first (1955), wide opportunities have been opened for modelling of real ice conditions and prompt fulfillment of orders by shipbuilding and hydrotechnical industries on the basis of data obtained from systematic experiments with models of structures to be operated in ice covered water areas.

The ice model basin of the Krylov ship Research Institute (length 45 m, breadth 6 m, and depth 1.7 m), where investigations of technical problems ere started in 1987, only slightly differs from similar facilities in other countries, but owing to a broad variety of dynamometer devices used in experiments provides

a means for carrying out tests in various ice conditions (Level ice, ice channel, broken ice, ridges) including:

- towing and self propelled model tests for ice breakers and ice;
- strengthened ships;
- towing tests of model offshore structures;
- measurement of screw-propeller characteristics in open water mode of operation in clear water, near an ice plane on free surface and in milling regime of interaction with ice blocks;
- ice loads estimates for screw blades, shafting system and blade-turning mechanism of controllable pitch propeller;
- investigations of static and dynamic methods of ice destruction by air - cushion vehicles and platforms.

Scaling from model experiments to full size conditions presents some difficulties due to the fact that so far it has been impossible for model basins to develop modelled ice with all physical and mechanical properties satisfying the similarity criteria for the processes under study. This problem demands serious consideration and cooperative efforts of specialists of ice research centers as well as collection of reliable full-scale information.

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NUMERICAL MODELS OF ICE DEFORMATION

Polycrystalline ice, a naturally occurring geomaterial, is of considerable interest in ocean engineering applications involving the indentation and penetration of structures and the use of ice as a structural material. Since the material is present in nature at temperatures very close to its melting point, terrestrial ice displays a highly rate and temperature sensitive behavior, more generally called creep. Ice also cracks easily under moderate to high rates of loading and is said to display quasi-brittle behavior. The transition from ductile (creep) to brittle behavior represents an important condition in engineering applications. Prediction of ice behavior within the ductile-to-brittle transition requires constitutive theories to describe the deformation (stress-strain) behavior of the material at laboratory-scale; and analyses which can be used to predict field-scale processes via numerical simulations.

This talk will present newly developed constitutive theories for the transient (time-dependent) creep and purely brittle behavior of ice. The transient creep theory is physically based, but phenomenological, uses internal state variables to model the evolution of the materials's microstructure during deformation, describes texture n=and stress-induced anisotropy under multiaxial states, and has been extensively verified against experimental data. On the other hand, the brittle behavior of ice, which is dominated by the nucleation (not propagation) of cracks, is described via a microstructurally based constitutive theory. The elastic anisotropy of the constituent crystals in a polycrystalline aggregate is the principal mechanism responsible for crack nucleation. The crack nucleation theory is used, in turn, to predict the accumulation of damage with loading and the associated (macroscopic) deformation behavior of ice, accounting for multiaxial and loading-history effects.

The talk concludes by presenting a finite element formulation for analyzing ice indentation involving transient creep as well as results from numerical simulations which consider problems of increasing complexity.

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ICE LOADS ON OFFSHORE STRUCTURES
(INVESTIGATIONS IN THE LENINGRAD STATE TECHNICAL UNIVERSITY)

This report deals with investigations that have been carried out at Leningrad State Technical University (LSTU) and devoted mostly to ice loads on offshore structures and partly to ice properties.

1. STRENGTH OF LAYERED MEDIA SAMPLES UNDER UNIAXIAL COMPRESSION
(Prof. Zvolinsky, N.V. - Inst. for Problems in Mechanics, Prof. Shkhinek, K.N. - LSTU).

Two dimensional solution has been found for compressed layered media samples. This media consists of thin elastic-brittle layers and extremely fine soft material between them.

Rectangular samples of this material is placed between press plates. It is assumed that sample's butt-ends are fixed to the plates and can't slide relatively them in horizontal plans. Lateral surfaces of sample are free from stresses. This solution has demonstrated that stresses in this sample are distributed most irregularly. Irregularity depends on the properties of layers, their angle of inclination, and sample's length-width ratio.

Strength-angle of inclination ratio is similar to that described in Payton's investigation.

2. ICE COVER INFLUENCE ON ADDED MASSES OF OSCILLATING BODY
(Dr. Bolshov, A.S., Dr. Matskevich, D.G., Prof. Shkhinek, K.N., LSTU)

Theoretical and experimental investigations resulted in elaboration of the method for calculation of added masses of bodies, oscillation under broken ice cover. It has been shown that if we know connection between added masses and

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frequency of oscillating in the absence of ice cover, it is possible to determine added masses with tue presence of broken ice.

3. ICE LOADS ON A SYSTEM OF PILES UNDER WATER LEVEL CHANGES
(Dr. Matskevich, D.G., Prof. Shkhinek, K.N., LSTU).

Kerr's solution for loads acting on a single pile is well known. However, the solution is inadequate for the system of piles, as load cannot be calculated by simple summation of Kerr's solution for each of the piles, because distortion of boundary conditions. Our approach was based on the idea of minimization deviation from exact boundary conditions. As a result solutions for the two-, three-, four-pile systems were obtained.

4. MATHEMATICAL SIMULATION OF ICE - VERTICAL PILE INTERACTION
(Dr. Matskevich, D.G., Prof. Shkhinek, K.N., LSTU

It has developed mathematical model of ice - vertical pile interaction. Ice is to be an elastic-brittle material. Computer program was developed for investigation process of ice crushing around the structure and ice load changing in a time.

The last time about 400 numerical experiments for different cross-section structures, ice properties, and boundary conditions has been conducted.

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DYNAMIC ICE-STRUCTURE INTERACTION DURING INDENTATION TESTS

To study dynamic ice-structure interaction during the crushing failure of ice, indentation tests were conducted by pushing a vertical, flat indentor into the edges of floating ice sheets. The indentor was supported on a movable carriage by means of three load cells to measure interaction forces at the ice-indentor interface. The displacements of the carriage and the indentor were measured separately. The indentor displacement relative to the carriage and provided comprehensive data on the dynamic ice-structure interaction during crushing failure of an ice sheet. Three basic modes of ice behavior were observed: creep deformation at low velocities, intermittent crushing at intermediate velocities, and continuous crushing at high velocities. Based on these measurements, a theoretical model is proposed which produces results similar to those of the experiments.

Because of the flexibility in the structural support system, the velocity at which the indentor moved was not always the same as that of the carriage. The dependence of effective pressure on the indentor velocity was investigated because the strain rate and the stress rate at a point in an ice sheet have a direct relationship with the indentor velocity. The maximum effective pressures measured at different indentor velocities were found to differ by a factor of 3 to 5; high pressures (8-13 MPa) were measured at low indentor velocities (<20mm s-1), and low pressures (1.2-4.3 MPa) at high indentor velocities (>100 mm s^1). The reduction in the effective pressure is believed to be caused by the change in failure mode from in-plane deformation at low velocity to out-of-plane brittle failure at high indentor velocity.

The data from this study were also used to compute the energy exchanges that take place during creep deformation and intermittent and continuous crushing of ice. The energy supplied by the carriage was partly stored in the structural

spring, partly converted to kinetic energy, partly dissipated in deforming and extruding the ice, and partly dissipated as heat in the damping mechanisms of the structure. Except for the heat dissipation, all other forms of energy were computed from the experimental data, and the heat dissipation was computed from the energy balance using the first law of thermodynamics. Plots of all forms of energy will be shown in graphical form, in which their relative magnitudes, time of occurrence, and interplay may be seen.

The main result of the energy exchange study is the thesis that intermittent crushing or ice-induced vibration takes place whenever there is an imbalance between the rates of work done by the carriage and the indentor and that there are no vibrations when these rates of work are equal.

The results of tests when intermittent crushing took place we analyzed to obtain the frequency of intermittent crushing failure. From the experimental results, a correlation was obtained between the average distance travelled by an indentor during successive failure events and the maximum relative displacement of the indenter with respect to the carriage during the loading phase of a cycle. From this correlation, the frequency of intermittent crushing can be obtained in terms of structural stiffness, ice velocity, effective pressure, indentor width, and ice thickness.

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FIELD MEASUREMENT OF PACK ICE STRESSES

Accurate measurements _in situ_ ice stresses were obtained in the pack ice of the eastern Arctic during the fall of 1988. Stresses were measured using biaxial vibrating wire sensors. these are cylindrical instruments which the principal stress components and the directions are determined from the resonant vibration frequencies of the wires. At one site about 200 m from the edge of a large multiyear floe, three sensors were installed at f=different depths to examine the vertical distribution of stresses within the ice. At another site, two sensors were installed at shallow depths in the multiyear floe near a freezing lead with an additional sensor in the first-year ice. Stresses in the multiyear ice far from the edge of the floe reached 150kPa during extreme deformation events. Near the edge and in first-year ice, they exceeded 350kPa on several occasions (400 kPa in one instance) when the ice failed very near the sensors. Thermally induced stresses at shallow depths in the multiyear ice were caused by rapid temperature changes and could be nearly as large as stresses observed during deformation. Often, the stresses at depth during these thermal events were of opposite sign to those near the surface. The vertical distribution of stresses varied with the type of deformation event, but the largest values were always observed in the upper half of the ice sheet. Stresses due to deformation were rapidly attenuated away from the edge of the floe. Near the edge, however, recorded stresses agreed well with those observed in the adjacent first-year ice. The sensor located in the first-year ice also experienced twice daily oscillations of about 50 kPa which are apparently tidal or inertially induced. Measurements of local ice motion with the radar transponder system allowed comparison of the stresses to the local strain field. Overall, there was very little agreement between stress and local deformation except during large deformation events.

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DYNAMIC ICE-FLEXIBLE STRUCTURE INTERACTION PHENOMENON

All existing approaches to the process of dynamic ice-structure interaction are possible to describe the relaxation mode, which consists of static loading phase and the movement in the crushed zone. But in the harmonic mode with high relative velocities all this approaches are not so useful.

Some results of theoretical and model researchers in connection with the analysis of existing data on dynamic interaction are presented. The new function of ice resistance makes it possible to analyze not only relaxation, but also the harmonic mode in terms of self-excited vibrations theory. There were developed some theoretical and experimental results for the case of prevailing frequency (one natural mode). An approach to the more complex analysis of real structures using the model is discussed.

After Maattanen (1977, 1981, 1984), who connected the possibility of self-excited vibrations occurrence with the non-linear dependence of the ice mechanical properties on the relative ice-structure velocity there appeared some attempts to present the ice resistance as a partly linear function of relative ice-structure velocity (Ranta, Raty, 1983; Toyama et al. 1983) or as a function of velocity and time (Karna, Turunen 1989).

There are some approaches to explain the phenomenon of ice-induced vibration: see, for example, the last ones - Eranti (1990); Wang, Xu (1990), Xu, Wang (1990), Sodhi, Nakazawa (1990), Karna, Muhonen (1990); etc. This problem is under research and discussions more than 20 years, but there is no valid and clear explanation of the nature of this phenomenon. In this article authors make an attempt to develop the model that gives loading time history using self-vibrations theory applied to flexible structure model.

General assumptions were worked out earlier by the first two authors (Vershinin, Iliady 1990). In this work the theory is completely modified using non-deterministic approach.

The numerical model of the process was developed and computer simulations with different model parameters were held. The results were compared with experimental data of structure modelling and real structures behavior in ice conditions.

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ICE LOADS ON STRUCTURES - A CASE STUDY

The Alaskan Bering Sea covers a large area with latitudes between 55 N and 65 N, off the west coast of Alaska. Most Bering Sea locations are in subarctic regions. Due to frequent rafting of sheet ice, the rafted ice in a number of Bering Sea locations can reach a total thickness of over 15 meters. Annual ice ridges with a total thickness of over 20 meters have also been observed. The ice conditions in many Bering Sea regions are similar to those around Sakhalin Island off the Pacific coast of the Soviet Union. In the mid-eighties, Exxon carried out a number of studies on the environmental conditions of the Bering Sea. Ice conditions, ice properties, and ice movement rates were carefully investigated for several regions.

In addition, model test data were processed to examine the accuracy of various ice load computation formulas for offshore structures. Random variables were then selected to represent environmental parameters and the differences between the measured and calculated forces. Based on environmental and model test data, a computer simulation program was developed to estimate rare ice loads for structures located in certain areas of the Bering Sea. In addition to providing estimates to rare ice loads, the simulation program was also useful for assessing the sensitivity of ice loads to various ice and structure input parameters.

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INTERRELATIONS BETWEEN GROWTH CONDITIONS,
SEA ICE STRUCTURE, AND SEA ICE PROPERTIES

Quantification of the properties of large areas of pack ice cannot be adequately resolved by direct observations alone. Yet, at present, remote sensing data provides only indirect information on the fundamental properties and processes that are needed to characterize a sea ice and its internal mechanical interactions as well as its external interactions with the atmosphere and ocean. Efforts to deal with this problem are summarized. Current approaches utilize buoy and satellite data to monitor ice and meteorological conditions. This information can be used to drive ice growth and ice property models that produce thickness distributions; sea ice salinity, temperature and brine volume profiles; and ultimately property profiles and composite characteristics. Examples of such procedures are presented using tensile strength and elastic modulus. Capabilities of the Alaska SAR Facility in contributing geophysical data useful in dealing with this general problem via the use of automated analysis procedures are described. Current problem areas remaining are related to variations in the amounts of frazil and gongelation ice, the effects of crystal alignments, uncertainties in ice thickness resulting from snow cover variations, and inadequate information on how to redistribute ice deformed during ridging events.

MEMORANDUM

A memorandum concerning cooperation on research in Ice Mechanics and Its Applications for consideration for incorporation in the cooperative agreement under discussion between the U.S.S.R. Academy of Sciences and the U.S. National Academy of Sciences

The First Soviet-American Workshop on Ice Mechanics and Its Applications was held in June 1991 (16-26) in Moscow, U.S.S.R. Representative Soviet and American delegations participated in the Workshop presenting a total of 34 papers. A list of participants is given in Appendix 1. The meeting was extremely successful.

During the Workshop the question of furthering future cooperation in ice mechanics and its applications between interested Soviet and American scientists and organizations was discussed. Taking into account the importance of the scientific problems under consideration, the mutual interest in and the benefits that would be derived from cooperative research in several aspects of ice and ice cover mechanics including the interaction of ice with structures, the members of the Workshop suggest that future cooperative investigations and programs be organized and that this organization take place within the framework of the program for U.S.-U.S.S.R. cooperation in scientific research on the level of the U.S. National Academy of Sciences and U.S.S.R. Academy of Sciences. It is further suggested that the U.S. National Science Foundation and U.S.S.R. Academy of Sciences add the subject area of ice mechanics to its approved list "Scientific Problems of the Arctic and the North" that are considered as appropriate for U.S.-U.S.S.R. Cooperation in the Field of Basic Scientific Research (NSF, 1991).

Possible forms for cooperative work between the U.S. and the U.S.S.R. might include the following:
- regular workshops every two years with the meeting site alternating between the two countries;

- joint research projects;
- joint field projects which might well accommodate several research projects;
- exchange of scientific information and the preparation of joint publications containing both original research and overall summaries of the existing knowledge base;
- exchange of specialists to prepare plans and programs for joint research, to carry out joint research, and to give lectures;
- exchange of graduate and post-graduate students in conjunction with coordinated research programs;
- support of the participation of specialists from both the U.S.S.R. and the U.S. in national and international scientific and engineering meetings on problems of the mechanics of ice and ice covers; and
- provision of a mechanism to facilitate contractual research between private companies, universities and governmental groups in one country with similar organisations in the other country.

To advance the above objectives, the Workshop members suggest that an Organizing Committee on Ice Mechanics and Its Applications be established to coordinate the proposed program. It is proposed that this group be composed of five members each from the U.S. and the U.S.S.R. with the nationality of the group chairman alternating at two years intervals. The intension is to create certain subgroups of specialists in the different fields of ice mechanics attached to the Organizing Committee. It is envisioned that the major programs carried out under the auspices of the Organizing Committee will be focused on specific research directions and will be both proposed and implemented by small groups of specialists.

Based on input from the Working Group members during the next two months, the Organizing Committee is specifically charged to prepare a preliminary description of a variety of proposed projects and programs that will then be submitted jointly in conjunction with the above organizational suggestions, to both the U.S.S.R. Academy of Sciences and the U.S. National Academy of Sciences for consideration at the next interacademy meeting.

We wish to emphasize that the following U.S.S.R. and U.S. scientists and engineers can in no way guarantee either financial or organizational support of the above proposal by their respective governments. They can only request that each government consider this proposal favorably.

Co-Chairmen of International Organizing Committee
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