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REPORT OF THE WORKSHOP ON
ARCTIC OIL AND GAS RECOVERY

held at

Sandia National Laboratories
Albuquerque, New Mexico
30 June - 2 July 1980

Edited by

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Preface

This report is the result of a workshop on Arctic offshore oil and gas recovery, held at Sandia National Laboratories, Albuquerque, New Mexico, on 30 June-2 July 1980. The workshop was organized and chaired by Dr. William M. Sackinger, Geophysical Institute, University of Alaska, as part of a Department of Energy contract to define research priorities for the technology related to Arctic offshore oil and gas production.

The workshop was preceeded by a report entitled, "A Review of Technology for Arctic Offshore Oil and Gas Recovery", authored by Dr. W. M. Sackinger. The reader is referred to that companion report, and the references cited in it, for a discussion of on-going Arctic research. This workshop report makes no attempt to reference completed or on-going research which addresses the problems identified herein.

At the workshop, participants first gave brief presentations in their area of interest. Then, two working groups were formed. The working group on Ice-related subjects was chaired by Dr. J. F. Prince, and the group on Soil-related subjects was chaired by Dr. M. A. Goodman. Members of each group are listed in the following pages. Both W. M. Sackinger and C. L. Shuster were non-contributory members of both groups; however, the section on instrumentation needed to accomplish some of the research objectives was written by them at the conclusion of the workshop.

The mission of the workshop was to identify research priorities without considering whether the research should be conducted by government or by industry. Nevertheless, at the end of the meeting the general discussion did consider this, and the concensus was that environmental properties should certainly be of concern to the government, that implementation of petroleum operations was the province of industry, and that overlapping, coordinated areas of interest include both environment and interactions of the environment with structures, transport systems, and operations.

An attempt to establish relative importance and a time frame was made after the workshop through the use of a survey form. The form and a summary of its results, and a discussion of its implications, are given in the following section.

Seldom does one encounter the degree of dedication displayed by the workshop participants. Their intensive commitment to the generation of a written plan for the Arctic offshore was motivated by the importance which they gave to this task. To all of the workshop contributors, and to Sandia Laboratories who hosted the workshop, I express my sincere gratitude, and I am sure that the implementation of the research discussed at the workshop will help ensure that Arctic offshore petroleum recovery is accomplished in a safe and economical manner.

August 29, 1980

W. M. Sackinger, Chairman
Arctic Oil & Gas Recovery
Research Planning Workshop

ARCTIC OIL AND GAS RECOVERY RESEARCH PLANNING WORKSHOP

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Ice-Related Group

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K.R. Croasdale
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Soils-Related Group

M.A. Goodman, Chairman

R. Prindle
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S. Green
E. Reece
P. Teleki
R.E. Smith
C.R. Williams

Summary of Results
Research Priority Allocation Survey

The survey form was distributed, with the first draft of the workshop report, to all workshop participants, to Department of Energy engineers who were unable to attend, to the State of Alaska, and to several engineers from industry who had indicated an interest. Constructive comments on the text were received from several workshop participants, and ten survey forms were received, including two from interested departments within the State of Alaska.

The cumulative results of the survey are shown in table S-I. The reader should bear in mind that the maximum possible project priority was $3 \times 10 = 30$; that abstentions are counted as zero but are indicated for each column; and that the number of replies was very sparse. Those who did respond, however, are, in my opinion, among the best-informed technical and research management specialists in the country on this subject of Arctic offshore technology.

Of most importance are the identification of projects with highest priority in the first time period, 1980-84, since these are of most immediate urgency. They are listed below in descending order of priority.

<u>Cumulative Priority</u>	<u>Project Number</u>	<u>Complete Description</u>
27	14	Conduct systematic stereo photography, laser overflights, and sonar measurement programs to obtain ridge profile distributions.
25	30	Conduct model tests and develop predictive theories for ice rideup on islands and structures.
23	24	Improve understanding of failure modes of a variety of ice features against various types of structures.
23	45	The mechanical properties of sediments on the sea bed should be determined.
23	16	Process available satellite imagery to provide data on multi-year ice movement and floe size distribution.

<u>Cumulative Priority</u>	<u>Project Number</u>	<u>Complete Description</u>
23	4	Conduct confined and unconfined tests to provide data on strength and stress/strain behavior of sea ice and freshwater ice as a function of environmental parameters and loading rates.
22	12	Measure ice drift velocity.
22	27	Describe local ice pressures as a function of ice mechanical properties, ice velocity, and contact geometry.
22	33	Evaluate impact loads upon structures from storm-driven ice floes.
22	59	Diagnostic instrumentation should be developed to measure the interaction of ice with prototype or operational artificial islands, structures, and subsea pipelines.
21	1	Verify hindcast models for Arctic areas that include the influence of ice cover on wave and surge generation, and shallow water effects.
21	3	Investigate mechanics of ice gouging as a function of sediment type.
21	13	Develop and verify regional ice dynamics models.
21	28	Investigate the characteristics and effects of rubble fields around structures.
21	48	A model of thaw and subsidence for a warm subsea pipeline buried in offshore permafrost should be developed.

At this time, there are two research programs oriented towards the Alaskan Arctic offshore. Industrial research, the first, is carried out both within corporate laboratories and by consultants. Much, but not all, of that research is jointly sponsored by several companies, through the Alaska Oil and Gas Association (AOGA). A description of AOGA research is given in Volume II of the companion report, "A Review of Technology for Arctic Offshore Oil and Gas Recovery." The second research program is the Alaskan Outer Continental Shelf Environmental Assessment Program (OCSEAP), supported by the Bureau of Land Management (BLM) through interagency agreement with the National Oceanic and Atmospheric Administration (NOAA). This Department of Interior program was established in 1975 to develop environmental information to be used in

the preparation of the Environmental Impact Statement (EIS) which preceeds each offshore lease sale. As such, it spans many areas of biological and physical science in the Arctic offshore, including some of the high-priority subjects listed above. It is a tribute to the program management of OCSEAP that some of these subjects are being addressed. Because of financial constraints on the OCSEAP program, however, several high-priority areas (such as ice/structure interaction) are not included, and those that are being studied are not operating at the level indicated as being needed in this report.

It is suggested that the Department of Energy initiate an Arctic offshore research effort as soon as possible. Identification of projects should be consistent with the priorities established above. Close coordination with both AOGA research and OCSEAP research is important, to ensure adequate and complete subject coverage without needless overlap. To accomplish the objectives described in this report, just in the priority areas above, will require substantial resources and a ten-year commitment. However, the opportunity of supplying as much as half of our national petroleum needs in the 1990's from the Arctic offshore depends upon having the best technology available for this important frontier area. Substantial economic benefits will be derived from developing and producing this resource, and the time available is barely enough. It is in the national interest to begin immediately.

- W. M. Sackinger

TABLE S-I

Results of Research Priority Allocation Survey

Research Project Task	1980-84		1984-87		1987-90	
	Priority	# Abstentions	Priority	# Abstentions	Priority	# Abstentions
1	21	1	19	1	16	1
2	15	2	13	2	8	2
3	21	1	18	1	13	1
4	23	1	17	2	12	2
5	15	2	12	1	11	1
6	19	2	18	1	10	1
7	19	2	12	2	8	2
8	16	3	11	2	10	2
9	18	2	12	1	10	2
10	14	3	10	3	8	3
11	20	2	17	1	15	1
12	22	2	20	1	18	1
13	21	2	17	1	14	2
14	27	1	18	1	16	1
15	17	3	11	2	10	2
16	23	1	19	1	15	1
17	13	2	13	1	12	1
18	18	1	14	1	14	1
19	13	4	10	3	9	3
20	15	1	9	2	9	2
21	18	3	15	3	13	3
22	18	1	21	1	13	1
23	19	2	17	2	17	2
24	23	2	17	1	14	1
25	16	3	11	3	9	3
26	17	3	13	3	11	3
27	22	2	17	1	15	1
28	21	2	16	1	13	1
29	17	2	17	3	17	3
30	25	1	19	1	16	1
31	14	3	11	2	9	2
32	9	4	7	4	6	4
33	22	1	23	1	17	1
34	20	1	15	2	13	2
35	12	3	14	2	9	2
36	10	3	15	2	11	2
37	12	3	11	4	7	4
38	11	3	13	3	11	3
39	16	2	11	2	10	2
40	12	2	10	2	8	2
41	11	3	10	4	9	4
42	9	4	9	4	8	4
43	7	3	7	3	7	3
44	19	2	15	1	14	1
45	23	2	20	1	16	1
46	13	3	11	2	9	2
47	19	1	15	1	14	1
48	21	1	19	1	13	1
49	16	1	15	1	13	1
50	19	1	17	1	14	1
51	18	2	14	3	13	3
52	17	2	20	2	16	2
53	16	3	12	3	11	3
54	14	1	17	1	18	1
55	11	4	9	3	7	3
56	11	4	8	3	8	3
57	19	1	17	1	13	1
58	20	2	15	1	13	1
59	22	1	19	1	17	1
60	15	1	14	1	17	1

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Arctic Oil and Gas Recovery Research Planning Workshop

Research Priority Allocation Survey

As we discussed briefly at the close of the workshop, it would be helpful if we had some indication of the relative importance of the research areas which have been identified, and also the timing urgency of the research. It is to the credit of the Soils working group that a step in that direction has been made.

Would you please use the following code in completing the matrix below; use any of the rankings as often as you wish.

- 3 - First Priority
- 2 - Second Priority
- 1 - Third Priority
- A - No Opinion

<u>Research Topic</u>	<u>Time Period</u>		
	<u>1980-84</u>	<u>1984-87</u>	<u>1987-90</u>
1. Hindcasts including ice & shallow water			
2. Date ice gouges			
3. Mechanics of ice gouging			
4. Stress/strain tests of ice			
5. In-situ flexural tests of ice			
6. Large and small scale ice tests (size effect)			
7. Analytical prediction of size effects			

<u>Research Topic</u>	<u>Time Period</u>		
	<u>1980-84</u>	<u>1984-87</u>	<u>1987-90</u>
8. Dielectric & electromagnetic properties of sea ice			
9. Frictional forces between ice and other materials			
10. Ice adhesion bond strength			
11. In-situ ridge geometry and properties measurements			
12. Measure ice drift velocity			
13. Regional ice dynamics models			
14. Remote sensing of ridge profile distributions			
15. Verify passive microwave imagery for multi-year ice			
16. Process satellite imagery to get multiyear ice movement and floe sizes			
17. Model of pack ice edge movement			
18. Compile pack ice edge movement data, verify model			
19. Field measurement of ice state			
20. Ship voyages to collect data on ice conditions			
21. Oceanographic/meteorological measurement program			

<u>Research Topic</u>	<u>Time Period</u>		
	<u>1980-84</u>	<u>1984-87</u>	<u>1987-90</u>
22. Side-scan sonar and bathymetric surveys			
23. Logistics bases at Barrow and Nome			
24. Failure modes of ice against structures			
25. Random flaws in ice; non-simultaneous ice/structure contact			
26. Model ice forces across wide structure front			
27. Describe local ice pressures vs. mechanical properties, velocity, geometry			
28. Rubble fields around structures			
29. Test structure verification			
30. Models and theory of ice rideup on islands and structures			
31. Predict wave runup and overtopping.			
32. Nonlinear surface effects in wave diffraction			
33. Impact of storm-driven ice floes against structures			

<u>Research Topic</u>	<u>Time Period</u>		
	<u>1980-84</u>	<u>1984-87</u>	<u>1987-90</u>
34. Ice action on slope protection systems			
35. Prediction of icebreaker penetration of ice ridges			
36. Models of multi-year ridge breaching by icebreakers			
37. Predict ice-pressure-induced delays in ship transit			
38. Ship penetration, resistance, and hull pressure during collision with ice features			
39. Ice forces on propellers			
40. Propulsion efficiency in ice.			
41. Ship-terminal interactions in ice			
42. Models of ship maneuvering in ice			
43. Predict ship performance in level ice			
44. Seafloor characterization			
45. Seafloor mechanical properties			
46. Seafloor geomorphological processes.			

<u>Research Topic</u>	<u>Time Period</u>		
	<u>1980-84</u>	<u>1984-87</u>	<u>1987-90</u>
47. Seismicity and resulting local ground motion			
48. Seafloor pipeline model for thaw/subsidence			
49. Frost heave in marine soils			
50. Foundations and pilings over subsea permafrost			
51. Effects of islands and causeways on coastal processes			
52. Location and extent of ice-bonded subsea permafrost			
53. Hydrate detection			
54. Active fault determination			
55. Theory and remote sensing of hydrate thaw during production			
56. Cementing of casing in hydrate regions			
57. Instrumentation for both laboratory and in-situ ice properties measurements			
58. Methods for rapid diagnostics of ice ridge profiles and consolidation			

<u>Research Topic</u>	<u>Time Period</u>		
	<u>1980-84</u>	<u>1984-87</u>	<u>1987-90</u>

59. Instrumentation to
measure ice interactions
with artificial islands,
structures, and pipelines

60. Ice surveillance system
for ship routing

Comments and suggestions about priorities:

Contents

	<u>Page</u>
I. Introduction	1
II. Ice-Related Considerations	3
A. Area-Specific Environmental Descriptions	3
- Ice Conditions	3
- Current Status of Data Sets	4
B. Non-Area-Specific Environmental Descriptions	6
- Ice Material Properties	6
- Standard Ice Test Procedures	7
- Bulk Ice Feature Properties	8
- Interaction of Ice with Other Materials	9
- Ice Gouging of the Sea Floor	9
- Oceanographic/Meteorological Considerations	10
C. Interaction of Environment on Proposed Operations	12
- Interaction of Ice on Structures	12
- Logic of Ice Interaction Predictions and Failure Modes	12
- Ice Mechanics and Yield/Failure Criteria	13
- Large-Scale Ice Forces	13
- Local Ice Pressures	14
- Ice Rubble Fields	14
- Ice Ride-Up	14
- Oceanographic Considerations for Arctic Structures	15
- Interactions Between Ships and Ice	16
- Resistance to Motion	16
- Level Ice	18
- Hull Structural Integrity	19
- Propeller Integrity	19
- Propulsion Efficiency	19
- Ship-Terminal Interactions	19
- Maneuverability	20
- Topside Icing of Ships	20
III. Soil-Related Considerations	20
A. Detailed Outline of Technology Relationships	21
B. Near-Surface Arctic Marine Soils	24
- Seafloor Topography	24
- Erosion	25
- Deposition	25
- Ice Gouging	25
- Soil Properties and Distribution	25
- Mechanical Properties	26

	<u>Page</u>
C. Earthquakes and Faults	26
- Seismicity	26
- Ground Motion	27
D. Design Problems	27
- Pipeline Routing	27
- Pipeline Construction	27
E. Production Platforms	28
- Pile Supported - Thermal Effects	28
- Gravity Structures	28
- Islands	28
- Impact on Coastal Processes	29
F. Deep Soils	30
- Distribution of Soils with Depth; Areal Extent	30
- Hydrates	30
G. Deep Soils - Earthquakes and Faults	31
- Ground Motion at Depth	31
- Fault Displacement	31
H. Hydrate Considerations for Production Wells	31
- Casing Loads	31
- Cementing	32
IV. Instrumentation Development	32
- Electrical Properties of Ice	32
- Ice Property Measurements	32
- Ice Ridge Properties	33
- Ice Location	33
- Ice Interactions with Operational Structures	33
- In-Situ Soil Properties	33
- Other	33
V. Research Project Tasks	35

I. INTRODUCTION

Production of oil and gas from the Arctic offshore, a frontier area, is being approached with traditional engineering methodology. For simplicity, this approach may be subdivided into three phases: developing an understanding of the physical environment, developing methods to describe how the environment will interact with proposed operations, and finally implementation of the operations.

Expedient petroleum development of the Arctic necessitates that simultaneous efforts be allocated to all three phases. It is, of course, understood that the third phase, implementation of operations, would be undertaken in any particular location only when sufficient environmental data and engineering methods are in hand to relate the information to the intended operation (i.e., an ice force on a gravel island, or an ice ridge load on a conical structure).

The judgement of what constitutes sufficient environmental data and engineering methods is complex; it depends strongly on such things as design methodology, assumed safety factors, and what is judged to be acceptable risk. In all phases of engineering, it is normal and expected that additional data on the environment, new ways of analyzing such data, new analytical tools, and--importantly--experience from ongoing operations, will lead to improved designs, designs that will be even better suited to the environment and optimized with respect to capability and costs.

There will always be differences of opinion as to information sufficiency or insufficiency. This is neither unusual or undesired. It insures that improvements will be made and information gaps filled. Such is the nature of all ambitious engineering ventures, as which Arctic offshore petroleum development can only be regarded. But, perhaps, technological sufficiency and insufficiency is a better way to evaluate whether a venture should go forward, rather than the more simplistic view which asks whether or not all the data gaps have been filled or all possible engineering topics have been addressed in detail. Technical work which addresses engineering improvements continues through the stage of sufficiency into and often throughout the lifetime of a planned operation.

The design of an offshore structure, for the Arctic or elsewhere, requires that analytical and experimental methods exist to estimate the loads that the environment will exert on the structure. These methods require that an adequate understanding of the environment be available to identify the most critical parameters and quantify their effects. To develop such an understanding, sufficient measurements of numerous physical parameters must be made to be able, ideally, to describe the environment in statistical terms. If it is desired to go forward with an offshore venture, in the absence of a statistically valid data base, more attention is required to determine extreme events or develop contingency plans to insure safe operation, should the design loads be approached.

The overall objectives of the workshop were to answer the following questions:

1. What are the problems crucial for the production of oil and gas from the Arctic offshore?
2. What needs to be done to solve these problems?

A large Arctic research effort in Canada and in the U.S. presently is underway to address many of these problems. This effort includes research at universities and government laboratories and also many programs of a proprietary nature conducted by industry. This report makes no attempt to reference completed or on-going research, which addresses the problems identified herein. The reader is referred to the companion report, "A Review of Technology for Arctic Offshore Oil and Gas Recovery," or other references in that report for a discussion of on-going Arctic research.

To accomplish these workshop objectives, workshop participants were divided into two working groups: ice and soils.

The ice-related group evaluated ice and oceanographic considerations, and compiled a list of research topics without assigning priorities or discussing responsibility for conducting research.

The soil working group first compiled a detailed outline of important problem areas relating to soil behavior and then prepared, from the outline, a working text concentrating on crucial problem areas only. In this context, the soils group felt that it was necessary to define the term "crucial" as used for their screening purposes and, therefore, the following definition was presented: "Crucial" was taken to mean "critically needed within a specific time frame for a problem that has not been solved before and cannot be easily solved with current technology".

While their text concentrated on crucial problems, some problems may be solved using traditional engineering methods once environmental data is obtained.

The complete soils outline is included as part of the report. The items on the outline are important and should be considered in any future Arctic offshore operations. The crucial items were selected for workshop purposes on the basis of the above definition and the written text addresses only these items.

The two working groups met as a single group on the last afternoon to discuss prioritization of the research topics and primary responsibility for conducting the research. Priorities were assigned as first, second and third based on a follow-up poll of workshop participants. The discussion of responsibility for conducting the research concentrated on general responsibilities of government and industry,

rather than responsibility for specific research items. It was felt that government should concentrate on characterizing the Arctic environment. Of principal interest is the systematic collection of critical environmental data, which can be made publically available for defining environmental exposure. Implementation of operations was specifically identified as an industry responsibility, and the interactions between the environment and structures, transportation systems, and operations were of overlapping governmental and industry concern.

II. ICE-RELATED CONSIDERATIONS - Area-Specific and Non-Area-Specific Environmental Description

In developing the description of the physical oceanographic environment, it is important to recognize that two categories exist for environmental characterization. First, there is a category that applies to broad geographic areas, such as wave heights in a particular offshore basin, or the extent of expected ice coverage or movement in a basin. Secondly, there are items that are believed to be non-area specific, but that are an essential part of the procedures used to estimate environmental loads on structures. Examples in the latter category are functions which relate material properties of ice to site-specific variables, as well as engineering properties investigations that relate ice to other materials.

A. Area-Specific-Environmental-Descriptions

Ice Conditions

An essential starting point for finely-tuned engineering oriented towards the Arctic offshore is the development of a statistical description of a number of aspects of the ice-dominated environment. The end results of such descriptions are commonly the estimation of rare events with recurrence intervals of 20 to 100 years. These values might indeed determine the design of a given structure. In other cases one might wish to know only the distribution of values existing at a given time (for instance the distribution of ice thicknesses) for use in an analysis of fluctuations in ice forces. Whatever the specific parameters of interest, to develop an adequate statistical characterization one must usually have a number of years of data as there are known periodicities in the state of the Arctic ice pack, in addition to the obvious seasonal changes and possible long-term climatic trends.

First, one should determine the kind of data needed to characterize the ice cover for engineering purposes. The two most important pieces of information would appear to be the ice thickness distribution and the ice velocity distribution, both as a function of time. Next one must know the types of ice involved, particularly the amount of multiyear ice and the number and size of ice islands, as these features can have high strengths and thicknesses, and large sizes. In the multiyear ice situation the geometry of the floes (especially, floe size distributions) can be important, as can the patterns of the thin ice in refrozen leads. (Ships use these thin ice areas as highways to speed their transit through the ice.) Data is also needed on the distribution of cracks in

the ice (both open leads and smaller fractures) as these will serve as useful input to models attempting to relate large scale (low-level) geophysical stresses to small scale (high level) engineering stresses. Also of importance in summer operations is the location of the ice edge, and particularly the occurrence of ice invasions (when high concentrations of ice drift rapidly into normally ice-free regions). Because of variations in sea ice types (crystal orientation, grain size, temperatures, salinities and snow cover), and related variation in mechanical properties, it is important to characterize the several types of sea ice in different regions and times of the year in connection with any field studies.

Current Status of Data Sets

In addition to about 30 years of historical ice charts, there are about ten years of satellite coverage of the Alaskan offshore. The historical ice charts are useful, but data is spotty and observations are usually only available during the summer shipping season. There are also large gaps in the satellite data due to limitations imposed by cloud-cover and darkness. The resolution of most of this satellite imagery is so coarse that many of the ice features of interest such as pressure ridges, rubble fields and multiyear floes cannot readily be distinguished. Of more fundamental importance, ice thicknesses cannot be directly observed in such imagery except to distinguish areas of very thin ice (less than 30 cm). Nevertheless this data has proved useful, has provided a general idea of ice conditions in the seas of the Alaskan Arctic, and has promising potential for reconnaissance tasks. Other higher resolution data sets (stereo photography, laser profilometry, and side-looking airborne radar) are available but currently provide limited coverage in time or space. However, even at best these data sets hardly allow refined estimates of rare events.

To improve this situation in the specific subject areas which have been measured, it is essential that the collection of such environmental ice data continue on a regular basis so that our observational time and space series can be expanded.

Ice Drift Velocities. Data on ice drift velocities should continue to be accumulated with added emphasis on coastal areas. Ice dynamic models which emphasize engineering applications should be developed on a regional basis. Satellite and ice drift buoy data should be compared with any modeling calculations to develop "verified" regional ice dynamics and thermodynamics models for the seas of the Alaskan Arctic. Progress is being made in this area at present. These models should then be run in the hindcast mode using historical barometric pressure fields to reconstruct past records of ice drift. Once verified, these models can then be utilized to develop improved estimates of drift velocity.

Ice Thickness Distributions. Temporal and spatial variation in ice thicknesses are poorly known in pack ice. Ice thickness data obtained by aircraft and satellites are not, at present, very useful for engi-

neering purposes. The best data come from submarine transits utilizing upward-looking sonar, but very little data exists for the shallow waters of the Arctic shelves. Even when transits of the shelves have been made, the submarines detour around deep ice ridge keels, resulting in a biased sample. Available data from the Gunard cruise has shown that the ice ridge keels nearer to the coast (the area of more immediate interest) are deeper than those found out to sea, and that the ice is more deformed near the coast. Combined laser profilometer and photo flights provide useful information on ice ridge thicknesses and support the conclusions based on the submarine data. However, at present there are only three years of laser profilometer data for the Chukchi and Beaufort Seas, and two years for the northern Bering Sea. Several years of aerial stereo photography data for the Beaufort, Bering, and Chukchi Seas have been acquired in industry proprietary programs. It is essential that systematic stereo photography, laser profilometry, and sonar sampling be continued. At the same time, efforts should be expanded to validate the calculated ice thickness distributions that can be generated using thermodynamic and ice dynamics models.

Amount of Multiyear Ice and Multiyear Floe Size Distributions. The percentage of multiyear ice can, in principle be determined from passive microwave imagery. However, the adequacy of methods remain to be subjected to detailed field verification. Existing satellite imagery should be used to study multiyear ice movements in the Chukchi and Beaufort Seas. Multiyear floes have also been distinguished in images obtained from aerial photography, side-looking airborne radar and synthetic aperture radar. Available imagery should be analyzed.

Location of the Ice Edge. The position of the ice edge can be observed on ESMR and SMMR imagery. Data available from these satellites' microwave system should be analyzed and combined with other satellite data and ice reconnaissance data to provide documentation on ice edge motions. These data should then be used to test models predicting the locations of the ice edge. Once a model is verified, it will be very useful in forecasting breakouts and ice edge locations in all of the Arctic offshore.

Lead and Crack Patterns. Large leads and cracks can be seen in present visual satellite imagery. A study of these should be carried out using fracture mechanics, and coupled with a modeling effort. The desired result would be an improved understanding of such fracture systems and our ability to forecast them.

Variations in Ice State. This refers to the crystal structure, composition and temperature of the sea ice as well as the state of the snow cover. These observations presently require field measurements, and they are time-consuming. Nevertheless, every opportunity to obtain such measurements should be made. There is also a need for improved equipment for making such observations.

Data Collection. The obvious solution to many of the problems associated with characterizing the nature of the ice cover is through

the use of satellite-borne remote sensing. It is clear that satellite technology is presently capable of assisting in the study of many of the problems described above: ice movement, multiyear and ice-edge identification, and pressure ridge patterns using synthetic aperture radar; ice type identification, ice boundaries and sea surface temperatures using passive microwave sensors; pressure ridge height distributions and ice type information using scatterometry. It would be useful if a polar-orbiting satellite containing such instrumentation were launched to obtain this data. The satellite instrumentation should be optimized for the study of ice; the data should be processed in real-time for rapid transmission to users in the field that are faced with operational decisions.

Although the usefulness of remote sensing cannot be overemphasized, direct surface observations of the ice properties are also invaluable. A logistics base is essential for conducting these in-situ measurement programs. Prudhoe Bay provides an adequate base for programs in the Beaufort Sea. However, logistics bases on the western coast of Alaska are extremely sparse. The Naval Arctic Research Laboratory (NARL) at Barrow provided an excellent base for work in the Chukchi and western Beaufort Sea. Because of the anticipated increase in field activities, as lease sales are scheduled in these areas, it is recommended that the government consider re-opening NARL. Logistics bases presently available in the Bering Sea are also limited, so that a similar capability at Nome would be desirable.

Efforts should be made to obtain detailed ice observations from every surface transit through the ice pack. For instance, specific icebreaker trips into pack ice areas should be utilized as observational platforms to collect systematic data on the thicknesses and properties of both deformed and undeformed pack ice.

B. Non-Area-Specific Environmental Description

Ice Material Properties

While considerable research has been devoted to material properties of sea ice, it is clear that much additional effort is required to improve the basic data about this complex material. Sea ice strength is a function of crystal size, salinity, temperature, crystallographic orientation, and strain rate. The present data base on ice strength may be sufficient to initiate Arctic operations, but is by no means adequate for optimum designs. Many years of careful materials science studies, directed at ice strength, are warranted. Details are being addressed by the Panel on Sea Ice Mechanics, Marine Board. Because most materials studies are concerned with structural materials, they concentrate on material properties in the linear elastic range, or at small deformation. However, the primary concern with ice is the load required to ensure rupture. Thus, material behavior up to rupture, and establishment of rupture criteria, are needed.

Both unconfined and confined (uniaxial and triaxial) ice strength tests should be carried out with appropriate variation in those para-

meters known to influence strength. It would be useful if these tests would develop additional data needed to characterize the stress/strain behavior of ice, including yield properties. Post-yield behavior should also be investigated. Strength and related mechanical property data are critical factors needed to relate basic ice properties to failure criteria for ice sheets, ridges, and ice rubble piles.

While confined and uniaxial ice compressive strength tests have been believed to be more critically needed, additional information regarding ice flexural strength indices would be helpful in the design of structures which will be designed to fail the ice in bending. To supplement existing beam-test data, additional large-scale beam tests, coupled with geometrical information on ice sheet and ridge thicknesses, may assist in design and design optimization of such structures.

The strength of ice as a function of ice volume (i.e., the size effect) needs additional investigation. Structure design work being done today is guided by a combination of in-situ measurements, large-scale test data, and small-scale test data. The majority of ice strength information is based on small-scale samples, frequently containing no more than one hundred cubic centimeters of ice. Since estimates of strength based on small-scale tests will result in conservative design, more cost-effective structures can be designed if additional information on size effects is obtained. While work is underway in testing larger ice samples, additional research is needed; such tests must be done in-situ in the Arctic itself, to avoid changes in temperature, brine content, and microcracks with time. Although such tests are expensive, a real cost benefit may be derived if one could demonstrate that ice is not as strong on the large scale as in small laboratory tests. Further, it seems reasonable to assume that correlations may be developed in well-planned research programs that enable small-scale strength values to be related to decreased realistic full-scale strengths.

Standard Ice Test Procedures

In testing the mechanical properties of normal columnar sheet sea ice, it has been established that throughout the sheet there are various sea ice types. It is believed that tests should be done on sea ice, investigating mechanical properties as a function of grain size and crystal orientation, so that appropriate methods to average the overall sheet strength can be obtained. However, it seems desirable that continued attention be devoted to the mechanical properties of low-salinity ice, since its naturally-occurring counterparts in the Arctic offshore (multiyear ice and ice islands) can represent the most severe ice design condition in areas where multi-year ice and ice islands occur. Finally, while laboratory tests should address sea ice mechanical properties as a function of temperature, these tests are hard to conduct near the melting temperature. To have increased confidence in results from laboratory-tested sea ice near the melting point, some field strength tests on warm sea ice would be desirable.

In all of the ice testing that may result in the future by various investigators, the past history of ice strength tests provides a caution. To be of most value, ice tests by different people and in different laboratories need to be able to be compared. Thus standard methods, unless there is strong reason otherwise, are encouraged. As a minimum, careful control of the tests should be sought, with a complete catalogue of test conditions. As a matter of technical need and interest, confidence in test methods is essential. Such confidence often hinges on the ability to compare independent test results. The choice of standards in ice test procedures is being pursued by the Committee on Ice Problems of the International Association of Hydraulic Research.

Bulk Ice Feature Properties

Pressure ridges may be the feature governing design for many types of structures. It will be necessary to predict ridge failure modes and resulting forces upon structures; therefore, in addition to understanding the mechanical properties of sheet ice, knowledge of the bulk engineering properties of ridges will be required to determine loads.

Some information on ridge sizes and composition are available. However, measurements of the following ridge characteristics at various times of the year and at different locations would be desirable.

First-Year Ridges

Geometry; size

- sail height/keel depth
- sail/keel slopes
- lateral variability/
spatial distribution

Composition

- block size/configuration

Consolidation

- interblock bonding
- refrozen zones, voids

Integration with Adjoining Sheet

- rafting, cracking

Multi-Year Ridges

Geometry; size

- sail height/keel depth
- sail/keel slopes
- lateral variability/
spatial distribution

Temperature Profile

Salinity Profile

Discontinuities, porosity

From these measurements, reasonable parametric bounds for engineering purposes may be determined. From the geometry and bulk composition aspects, it is possible to assess ice/structure interaction problems and select favorable structural configurations. Ice failure modes may be predicted by analysis of ridge composition and consolidation characteristics. Temperature and salinity data will be used to calculate brine volume from which strength indices and other mechanical properties may be estimated. Other direct measurements of mechanical properties of ridges are discussed in connection with icebreaker operations.

Interaction of Ice with Other Materials

The foregoing discussion emphasized the desirability of a larger data base for ice material properties. However, ice will be interacting with other materials in most contemplated Arctic offshore operations. This interaction will result in both large-scale forces and local forces on fixed structures and on ships, but these forces will be influenced by the interaction between the ice and the material used at the surface of the structure or ship. Thus additional engineering data is desired on the frictional forces and abrasion between ice and steel, ice and concrete, and ice and other materials that might be used to coat Arctic structures. Knowledge of adhesion forces or forces required to break a frozen bond between ice and various construction materials would also help optimize designs and, perhaps, simplify methods to prevent such bonds from occurring.

Ice Gouging of the Sea Floor

A thorough understanding of ice gouges is important to the design of sea floor pipelines. Ice gouging is also undoubtedly a very important process in determining the properties of the sea floor sediments as the upper few meters of this material is being repeatedly reworked by the ice relative to the low rate of sedimentation. Current information on gouging is available in the Alaskan Beaufort Sea to water depths of approximately 35 m. Gouging is extremely common in this zone with the deepest gouge currently recorded having a depth of 3.6 m. Current research shows that although gouging initially appears to be a chaotic phenomena, it is well-behaved statistically and its geometric characteristics can be readily quantified. Comparisons between gouging along the Alaskan coast of the Beaufort Sea and that observed off the Mackenzie Delta just to the east reveal appreciable differences. It is to be expected that similar differences may be observed in the gouges in the Chukchi Sea and the north Bering Sea (although statistical techniques successful in one area will undoubtedly be useful in the others).

It is essential that systematic side-scan sonar and precision bathymetry surveys be continued in the Beaufort Sea out to water depths of 80 m (gouges were not found in waters deeper than 80 m off the Canadian coast). Although petroleum operations in such deep waters of the Beaufort Sea may be beyond present technology, the gouges in deep water provide a historical imprint of hundreds of years of significant ice features upon the sea floor, which will be useful in examining gouging statistics. Similar studies should be immediately started in the Chukchi where gouging is presumably extremely common. The studies in the Chukchi Sea may require the use of an icebreaker, with several field seasons of operation because of the large area involved. Of extreme importance are replicate measurements of the same areas year after year, to provide information on the rates of gouge formation. In this way it will be possible to calculate the temporal recurrence intervals of gouges of different depths. Any other promising technique which can offer insight on the history of ice gouging should be pursued. Studies should also be undertaken on the mechanics of gouging in different types of sediments. Field observations, physical modeling and

scale modeling should all prove useful. Such studies combined with information on the state of ice in pressure ridge keels and in ice islands should give insight into the maximum possible gouge, in a given sediment, region, and recurrence interval.

Oceanographic/Meteorological Considerations

Oceanographic and meteorological parameters must be considered in planning Arctic offshore development because open water conditions can occur for at least portions of the year in all basins. Table I lists the primary parameters of interest. These parameters should be described in terms of both normal and extreme conditions.

Normal conditions describe the range of typical conditions throughout the year as a function of month or season. This information is used to plan floating drilling and construction operations, estimate scour and erosion around fixed structures, and to estimate fatigue. For offshore areas of Alaska, the Climatic Atlas published by the BLM/NOAA OCSEAP provides a comprehensive summary of normal conditions based on historical ship observations and data from coastal weather stations. However, extreme wave height estimates in the Climatic Atlas are misleading. The atlas uses Thom's method to predict extreme wave height distribution. This method, which uses inappropriate statistical analysis procedure, and does not consider fetch limitations or shallow water effects, has been shown to overestimate significantly the extreme wave heights in other areas. Further, additional data on normal conditions, especially in the western Bering and the Beaufort Seas, would be desirable to optimize operations because the existing data base is sparse. It is expected that measurement programs will be conducted to supplement the Atlas information.

Extreme oceanographic conditions typically are described in terms of exceedance probabilities or return periods. The information is used to calculate design wave loads, set free-board elevation, estimate erosion and scour, and predict damage to slope protection for gravel islands.

A reliable long-term data base would be ideal to develop estimates of extreme conditions. Since such a data base is typically not available for wave heights, currents, or storm surge, the accepted procedure is to develop long term statistics using hindcasting. Hindcasting typically involves the following steps: 1) review historical meteorological data; 2) select the most severe storms; 3) hindcast wind, wave, surge, and current during the storms; 4) use statistical methods to extrapolate values associated with small exceedance probabilities from hindcast values.

In order to have confidence in this technique, the hindcast model should be verified with measured storm data. Deepwater spectral hindcast models for extra-tropical storms have been developed and verified for other OCS areas. However, the influence of ice cover on wave generation, and shallow water effects, should be included in hindcast models for most Arctic areas. Measurements will be required to provide data

Table I. Typical Oceanographic and Meteorological Parameters of Interest

WIND

1. Sustained windspeed
2. Gust Speed
3. Direction

WAVES

1. Significant wave height description
 - a. Significant wave height
 - b. Significant wave period
 - c. Direction
 - d. Swell height and period
2. Non-directional spectral description
 - a. Frequency spectrum of wave energy
 - b. Primary (and secondary if swell) wave direction
3. Directional spectral description
 - a. Frequency and directional spectrum of wave energy

CURRENTS

1. Current speed (tidal and wind-driven)
2. Current direction
3. Depth of measurement

SURGE/TIDE

1. Astronomical tide variation
2. Storm surge elevation

PHYSICAL OCEANOGRAPHIC

1. Salinity
2. Water temperature

METEOROLOGICAL

1. Barometric pressure
2. Air temperature
3. Relative humidity
4. Precipitation
5. Visibility and ceiling

OTHER

1. Marine growth

for calibration and verification of such Arctic hindcast models. Because storm data are required, measurement programs should typically be planned for more than one season. Measurements should include wave spectra data and other parameters listed in Table I for which reasonable bounds cannot be determined from other sources. The data should also be analyzed to provide additional information on normal conditions. Information on water currents throughout the winter season permits the assessment of erosion of gravel islands or their effect on other planned operations.

Wave and surge/current hindcast models should be developed and verified with measurements. Although existing models may be adequate in some areas, the following topics should be considered:

- Ice/Wave Interaction - The effect of broken ice cover on wave generation should be assessed in order to define fetch. A related problem is the maximum ice floe size and floe motion during a storm.
- Shallow Water Effects - Because of the wide, shallow shelves typical of many Arctic areas, shallow water effects on wave generation and propagation must be considered. Models of refraction, diffraction, breaking and bottom effects should be applied.
- Pack Ice Effects on Storm Surge - The effects of ice cover on storm surge generation should be investigated. Maximum water-level elevations in the presence of ice are needed to determine the potential impact zone on structures.

C. Interaction of the Environment on Proposed Operations

Interaction of Ice on Structures

Structures that withstand the lateral forces imposed by ice have been used for many years. Artificial gravel islands have been built to withstand the ice regime of the Canadian Beaufort Sea out to the 20 meter water depth. The design of these islands has been based on the extensive research on ice/structure interaction which industry has been conducting during the last ten years. This research has included: laboratory testing of ice to better understand ice mechanics; field tests of in-situ ice strength; model tests; field measurements around actual artificial islands; and the development of theoretical models.

Logic of Ice Interaction Predictions and Failure Modes

To predict ice interaction phenomena with structures, an understanding of both ice failure modes and ice mechanics is required. Given sufficient driving force, ice which moves against a structure will fail locally in the failure mode requiring the least local force. For sloping structures, the ice sheet fails in bending; for vertical structures, the ice either fails in crushing or by buckling; for wide structures, the ice which fails initially against a structure may not clear

away, and subsequent action takes place against the ice rubble in a mixed mode failure involving both crushing and bending. If ice is frozen to a sloping structure, bending failure cannot take place without first the adfreeze bond being broken. Failure of an ice ridge may be by vertical bending, by crushing, or by flexural bending in a horizontal plane, depending upon ridge dimensions and properties.

Our classification of failure modes of ice is fairly well advanced. However, additional quantitative knowledge of the failure modes of a variety of ice features against various types of structure and ship surfaces is necessary.

Ice Mechanics and Yield/Failure Criteria

In order to predict ice forces for particular ice failure modes, a good knowledge of ice mechanics is required. Given complete knowledge of ice material properties, it should be possible to develop relevant and reliable yield or failure criteria from which ice forces can be predicted. Considerable research is being undertaken on this topic, most recently using plasticity analysis. Approaches using fracture mechanics are also being tried.

Sea ice material properties of importance for a fracture mechanics approach include the compressive and tensile yield strength, fracture toughness (mode I, mode II, K threshold), creep and fatigue coefficients, Young's modulus, and Poisson's ratio. These are functions of the material and preexisting cracks. Ice geometry is important for evaluating the effects of stress concentration sites.

Because these approaches are theoretical and assume "perfect" material behavior and usually simultaneous contact, they are likely to be conservative. Additional understanding of how valid these approaches are for real situations is desirable. In particular, the effects of random flaws in the ice and non-simultaneous contact should be further studied.

Large-Scale Ice Forces

Knowing the ice forces for particular failure modes enables the total ice force on a structure to be predicted, if the ice clearing forces can also be predicted. For narrow structures, ice clearing forces can be calculated using kinematic models which are dependent on structure shape, ice piece sizes and friction. Such models for total forces have been calibrated in both large and small-scale ice basins and are now considered fairly reliable. However, a test structure would be very desirable to confirm such large-scale ice force predictions.

For very wide structures which may also be in deeper water and therefore could interact with thick ice features, the total ice force may be limited by the driving force. Typically the "driving force" may be controlled by the average ridge initiation and building forces acting

behind a thick wide ice feature such as an ice island. Therefore, for deeper water and large structures, additional knowledge of average ridge-building forces across a wide front is required.

Local Ice Pressures

The design of the outer wall of a steel or concrete structure is based on the maximum local ice pressures which can be expected. For ice-breaking vessels, codes for designing for local ice pressures have been established based on experience and testing. However, ships can ram the ice at speeds greater than 5 m/sec, whereas it is unlikely that stationary structures will be subject to ice velocities greater than about 1 m/sec. Because of the dependence of ice strength on strain rate, local ice pressures developed for ship design may be conservative for structure design. A research program should be undertaken to develop design values of local ice pressures as a function of ice mechanical properties, ice velocity, and contact geometry.

Ice Rubble Fields

As already discussed, when ice acts against a very wide structure, much of the failed ice cannot clear around the structure, and therefore an ice rubble field is formed. For structures in shallow water or with gradually sloping sides, the rubble may become grounded and become a feature against which the oncoming ice acts. A better understanding of several aspects of ice rubble around structures would assist in the design of offshore structures:

- * Ice rubble geometries for various ice movement and thickness distributions.
- * The depth of grounding of ice rubble as a function of ice thickness and other relevant parameters
- * The ice forces required for continued rubble field formation (similar to ridge-building forces).

Ice Ride-Up

For low-freeboard structures with slopes, there is a possibility of ice riding up onto the surface of the structure. Research has already been conducted into this phenomena and certain simple models have been developed. It appears that by utilizing suitable beach geometries and freeboards, ride-up onto the working surface of the structure can be avoided (particularly for production structures which will generally have higher freeboards than exploration structures).

For optimization of the design of structures to resist ride-up, it would be desirable to conduct model tests and develop predictive theories for ice ride-up, and test specific geometries and ride-up defense techniques.

Oceanographic Considerations for Arctic Structures

Depending on structural configuration, geographic area, and the relative severity of oceanographic and ice criteria, wave loads may be greater than design ice loads in some Arctic offshore locations. In addition to wave and current loads, oceanographic considerations for steel or concrete structures include wave erosion and current scour of the foundation, wave runup on structures with sloped sides, and wave crest elevation to determine deck height for tower structures. For gravel islands, erosion due to waves and currents must be assessed. Freeboard may be determined by wave runup and overtopping considerations, and expected wave conditions will affect the selection of slope protection.

Procedures for determining wave loads on structural members of small diameter with respect to wavelength are well-defined. As member diameter/wavelength increases, diffraction effects become more important. Linear diffraction theory has been developed and used to design large gravity structures in other areas of the world. However, wave theory including non-linear surface effects, which may be important for conical structures in shallow water, has not yet been developed. If wave runup and overtopping are determined to be critical to structure design, model tests should be conducted to obtain more accurate estimates of these parameters.

Analytical models to predict erosion from waves and currents are presently available. Additional refinement of the analytical procedures or model tests may be required prior to final design.

Arctic production gravel islands will be installed for an estimated life of 20 to 25 years. Adequate slope protection will be required to prevent erosion of the island. While guidance on sizing slope protection is available, additional model tests and studies will be performed prior to final design and construction to estimate damage to slope protection from ice.

Impact loads from storm-driven ice floes should be evaluated. These loads are expected to be of greater importance in areas of the Bering Sea where structures will not be designed for ice conditions as severe as in the Beaufort Sea. Maximum ice floe size during storms, floe motions, and impact loads should be evaluated.

Analysis techniques are presently available to provide estimates of wave loads, erosion, and runup that are suitable to determine structural feasibility and preliminary configurations. Refinements of analytical techniques and model tests would improve final designs. Research topics of general importance in this respect include:

- * Develop improved techniques to predict wave runup and overtopping on gravel islands as a function of different structural configurations and slope protection. Analytical models, empirical relationships, and model tests would be involved.

- * Investigate, using model tests or theory, non-linear surface diffraction effects in calculating wave loads on wide structures.
- * Evaluate floe size and motions in the pack during storms. (Ice impact loads on structures can be evaluated using existing analytical procedures, provided the mechanical properties of the ice are established.)
- * Conduct model tests and analytical studies to investigate ice actions on several candidate slope protection systems.

Interactions Between Ships and Ice

Ships will be required to support exploration and production of Arctic offshore oil in some of the following roles:

- Bulk energy transportation - tankers
- Logistical support - supply/work boats
- Construction support - pipelayers/dredges

To design ships to meet performance requirements in ice-covered waters, it is necessary to have available the technology to relate the ships' performance and reliability to the parameters which may be controlled by the designer. For example, assuming a knowledge of the properties and extent of ice cover in a particular zone, an "owners' requirement" to achieve a given turn-around for a tanker time along a route in that zone implies a concomittant requirement to achieve an average speed. The designer can control ship shape, dimensions and power. A relationship between speed and the design variable (ship shape, size and power) and the environmental variables is required to insure a tanker system design which achieves the desired turn-around time. In the following sections the current state of the "models" which describe the relationship between performance and reliability measures, designs, and environment-controlled variables will be briefly stated. Needs for improving these "models" will be identified. The performance and reliability factors which are considered important are:

- ship transit system
- hull structural integrity
- propeller/appendage integrity
- propulsion efficiency
- maneuverability
- ship terminal interaction
- topside icing

Resistance to Motion

Table II lists categories of resistance to ship motion caused by ice, with the applicable relevant variables.

TABLE II

ICE RESISTANCE TO SHIP MOTION

<u>Type</u>	<u>Major Variables</u>	<u>Math Models</u>	<u>Physical Models</u>
Level Ice Resistance	ice thickness speed friction factor ice strength hull size hull shape snow cover	ok ok ? ? ok ? ?	ok ok ok ? ok marginal proof ?
First Year Ridge Resistance and Rubble Field Resistance	cross sectional area degree of consolidation hull size hull shape ship speed	no nonproprietary data full scale	attempted but no model/ full scale correlation
Multi-Year Penetration Resistance	cross sectional area strength hull size hull shape ship speed	no nonproprietary full scale data	no nonproprietary full scale data
Resistance augmentation due to Lateral Forces	lateral force level ship length flare angle	no full scale data	no full scale data
Resistance in Broken Ice (icebreaker track)	speed ice thickness track width	available	ok ok ok

? denotes inadequate correlation between model and full scale

Level Ice

Level Ice

The most widely studied resistance category is level ice. Nonetheless, totally satisfactory tools to predict the influence of engineering properties of ice, of design-controlled ship variables or to estimate ship transiting performance are not yet in hand. Specifically, the capability of model/full-scale correlation studies to predict accurately the effect of ice strength, hull shape and snow cover needs to be verified. However, today, it can be said with confidence that full scale resistance in snow-free level ice can be predicted for a given design, to within $\pm 10\%$ at elevated speeds (in excess of 2 m/sec) and to within $\pm 40\%$ at very low speed.

- First-Year Ridges

In the Chukchi and Bering Seas, first-year ridges are the predominant feature. The development of mathematical models is underway and physical simulations have been undertaken. Although some proprietary data exists from tests conducted in the Baltic Sea, there is little publicly-available data which demonstrates correlation between physical models, math models, and full scale performance in ridges. For ship systems in which delays produce high economic penalties, current techniques for predicting ridge penetration resistance are inadequate to insure proper power selection at the design stage. This should be improved.

- Multi-Year Ridge Resistance

Ship systems operating in the Beaufort Sea, the western part of the Northwest Passage, and in some areas of the Chukchi Sea should be competent to breach and penetrate normally-encountered multi-year ridges. Models have not been developed to characterize this interaction. Attempts at physical simulation of multi-year ridge breaching by ships have been made, but no full-scale field data has been accumulated which simultaneously incorporates an adequate characterization of ridges to permit model/full-scale correlation. Development of ship-ridge breaching models is necessary for design of energy transport systems where some multi-year ridge encounters are virtually unavoidable.

- Resistance Augmentation Due to Lateral Forces

In the Beaufort, Chukchi and Bering Seas convergence of the ice cover is frequently observed. This generates an additional component of resistance due to increased side friction on ships. Today's ships can be stopped in such pressured ice, and since pressured ice is usually in motion, they then may be carried aground and damaged. Even temporary stoppage due to such resistance augmentation may cause delays, resulting in economic penalties. No tool presently exists to predict such delays, and the ship power or special designs necessary to overcome them. Predictive methods should be developed and innovative ship designs considered which could solve this problem.

- Resistance in Broken Ice

Extensive past research and operating experience have provided an adequate understanding of this situation.

Hull Structural Integrity

Adequate tools exist today to analyze and synthesize the structure of ships under the influence of known loads. However, methods for estimating the loads and local pressures arising at the interface between the ship's hull and an ice feature, caused by a collision with the ice feature, are inadequate. Preliminary work on this problem is underway, which combines a collision simulator with an ice penetration pressure model. The collision simulator is a state-of-the-art, combined two-floating-body motion simulator. However, a well-corroborated model for high-energy penetration resistance and pressure still requires development.

Propeller Integrity

Loss of propeller blades is not infrequent on even the most powerful icebreakers. In an area of moving ice cover, loss of propeller blades can transfer control of the ship from the operator to the environment. Existing ice force models for propellers are extremely simplistic and require full scale corroboration. Physical modeling tools are being developed at a very slow pace. Accelerated development of mathematical and physical models, together with full-scale corroboration trials are essential for designing reliable propulsion systems.

Propulsion Efficiency

Losses of propulsion efficiency due to ice interaction are ill-defined, but are believed to be significant. To fairly bound the problem for future assessment of priorities, it is doubtful that more than 10-20% improvement in ice-breaking propulsive efficiency could be achieved by significant research.

Full-scale and model-scale propulsion experiments in ice could be carried out on a very high-powered ship (Polar Star/Sea) to understand the importance of this problem in future high-powered ships.

Ship-Terminal Interactions

When ships enter terminals repeatedly, they necessarily break the ice in their path many times. As a result of accelerated refreezing of the open water which they create, ice conditions are cumulatively more severe than would exist had the ship not traversed the area.

Models to predict the severity of this increase have been developed and corroborated under climatic conditions much less severe than found in the Arctic offshore area. These models need to be extended and corroborated for climatic conditions of the Arctic offshore.

Maneuverability

Cargo ships require a certain degree of maneuverability in ice to avoid hazards, and to enter terminals. Supply ships and work boats must be maneuverable in ice, in order to load and unload near drilling ships and platforms. While general ideas exist concerning which parameters influence ship maneuverability in ice (see Table III), no quantitative model exists which permits the designer to choose values of these parameters to achieve the desired maneuverability (e.g. turning circle).

Mathematical and physical modeling techniques should be developed for determining the influence of environmental and design-controlled variables on maneuvering.

Topside Icing of Ships

Topside ice constitutes a serious hazard only to ships which have low intact stability characteristics such as fishing boats and tugs. Icebreaking ships in excess of 5,000 tons displacement should have adequate stability. Large tankers will have little difficulty insofar as the hazard of ship capsizing. Small, low freeboard work vessels will have some problems unless care is taken in selection of stability requirements. Designing for the topside icing problem under these circumstances is considered to be within the state-of-the-art.

TABLE III

Factors Influencing Ship Maneuverability in Ice:

- Turning Moment
 - Flare at the Contact Points in a Turn
("shoulders" and "quarters")
 - Level Ice Breaking Capability
-

III. SOIL-RELATED CONSIDERATIONS

The soils outline is organized into two major parts, Part I on near surface soils as they relate to pipelines, structures, and seafloor facilities and Part II on deep soils as they impact on structure and well casing design. Each part is then divided into two main sections, Section A on natural soil conditions and Section B on design problems. In effect, Section A considers important data and information that cannot be controlled and Section B addresses items that can be controlled and influenced by engineering and operations.

A. Detailed Outline of Technology Relationships

ARCTIC SOILS

I. Near Surface (Pipelines, structures & seafloor facilities)

A. Conditions Given By Nature

1. Soil Properties & Distribution

- a) Mechanical - static vs. dynamic
- b) Thermal
- c) Chemical

2. Seafloor Topography

- a) Slopes
 - b) Erosion features
 - c) Deposition features
 - d) Ice scours
- } morphology

3. Earthquakes & Faults

- a) Seismicity (geologic history) - hazard exposure
- b) Projected risk
- c) Ground motion - instrumental vs. effective

B. Design Problems

1. Pipelines (power cables, etc)

- a) Routing
- b) Construction
- c) Operation

2. Production Platforms

a) Pile supported

- 1. Axial/lateral soil resistance - structural, environmental, and soil loading
- 2. Installation techniques - installing piles, temporary support for structure during pile installation
- 3. Soil loading
- 4. Thermal (natural/operational)

b) Gravity structures

- 1. Stability and bearing capacity
- 2. Installation techniques - installing piles, temporary support for structure during pile installation

- 3. Soil loading
- 4. Foundation erosion
- 5. Settlement - elastic deformation, consolidation
- 6. Thermal
- 7. Ballast material availability
- c) Islands (mudline down - for structures)
 - 1. Stability and bearing capacity
 - 2. Installation techniques - installing piles, temporary support for structure during pile installation
 - 3. Soil loading
 - 4. Foundation erosion
 - 5. Settlement - elastic deformation, consolidation
 - 6. Thermal
 - 7. Ballast material availability
 - 8. Perimeter protection
 - 9. Island deformation
 - 10. Salvage
- d) Complaint towers (assumed not applicable in some parts of the Arctic)
- e) "Mobile" platforms (seasonal)
 - 1. Anchoring
 - 2. Support
- 3. Exploration Platforms
 - a) Gravity - see above
 - b) Islands
 - c) Mobile platforms (including drillships)
- 4. Seafloor and Subbottom Well/Production Facilities
 - a) Siting
 - b) Construction
 - c) Operation and maintenance
- 5. Causeway and Other Shore Facilities

C. Environmental Considerations

1. Impact on Coastal Processes
 - a) Ecological impact
 - b) Sedimentation
 - c) Thermal effects
2. Off-Coast Processes

II. Deep Soils (Well Casings)

A. Natural Conditions

1. Properties
 - a) Mechanical
 - b) Thermal
 - c) Chemical
2. Distribution With Depth; Areal Extent
 - a) Depositional history
 - b) Thermal history
 - c) Permafrost (continuous & discontinuous)
 - d) Hydrates
 - e) Abnormally pressured gas
3. Earthquakes and Faults
 - a) Seismicity
 - b) Projected risk
 - c) Ground motion - deep vs. surface instrumentation
 - d) Fault displacement - tectonic, non-tectonic

B. Well Design Problems

1. Drilling
 - a) Conductor installation/stability
 - b) Permafrost
 1. Hole sloughing
 2. Internal freezeback (shutdown)
 3. Well spacing considerations
 4. Curved conductors/directional drilling
 - c) Hydrates
 1. Detection
 2. Gas cut mud

2. Production Wells (multiple wells)

- a) Well spacing requirements
- b) Permafrost
 - 1. Thaw extent
 - 2. Imposed casing loads
 - a. axial
 - b. radial
 - 3. Casing strain limits
 - 4. Seafloor deformation
- c) Hydrates
 - 1. Decomposition extent
 - 2. Casing loads
 - 3. Cementing

B. Near Surface Arctic Marine Soils

Seafloor Topography

Reconnaissance of the seafloor for the types and distributions of lithological units and structural setting is the first task in determining the regional hazards existing in a given area. The majority of these hazards are not limited to the Arctic but have been encountered in other offshore areas. The reconnaissance tools conventionally used are high-resolution seismic profiling, side-scan sonar surveying, sediment sampling, and shallow coring. In cases where erosional and depositional processes are to be investigated, water currents and sediment transport rates should be determined.

One important geologic problem occurring on the surface and shallow subsurface is mass movement on the seafloor. Features currently observed in seismic and sonar records, such as failure zones in sediment masses, are associated with gravitational and local deformational processes such as tectonics and growth faults. Gravitational processes are particularly active on steep slopes, with instabilities such as slumps, slides and creep. Rotational seafloor mass movement is commonly associated with growth faulting. Channelized flow of sediment often occurs in areas of soft unconsolidated sediments and high sedimentation rates, even with very gentle slopes.

Characterization of mass movement features include: 1) determining the age of mass movement features; 2) determining where the plane(s) of failure exist and the mechanics of movement; 3) predicting rates of movement. In the Arctic offshore these processes may further be modified by thermal conditions, by the inclusion of ice in interstitial pore space, and by the seasonal fluctuations or presence of such phenomena as ice sheets, currents, tides, and waves.

Erosion

Erosional processes are principally current and wave induced. Manifestations include migration of sand-wave fields, scour by storm-tide currents in coastal setup, gouging due to ice keels dragging on the bottom, scour around grounded ice features, and erosion by meltwater descending in coastal areas from the adjacent land.

In Arctic areas, present knowledge of hydraulics and sediment transport processes is generally adequate during open water conditions. Some variation in the inertial aspects (such as Reynolds similitude) are expected as a function of water temperature. In very shallow waters, ice ride-up on beach slopes may cause permanent changes. Warmer spring flood waters may cause coastal erosion. Erosion processes worthy of attention include: (1) the current regime and resulting sediment movement under ice, and (2) the rate and effect of coastal flooding. Existing instrumentation is capable of such studies. Similar erosional processes offshore are difficult to study under pack ice. Current measurements through the ice from ice floes have been made; however, the interaction of current with the ice sheet and the seafloor is poorly understood. Placement of current meters and sedimentation measuring devices below the ice should be considered.

Deposition

Depositional processes generally do not represent a hazard or obstruction except near harbor entrances, in dredged channels and other waterways. Because the rate of sedimentation is closely coupled to river efflux, the most significant areas will be near river deltas such as those of the Colville, Kuskokwim, and Yukon rivers. Rapid sediment accretion in such areas incorporates organic material which in turn generates biogenic gas. Gas escaping from below the seafloor causes small "craters" and large slumps.

Ice Gouging

A unique Arctic problem is ice scour of the seafloor. Previous research has concentrated on mapping the extent, density and depths of scours caused by keels of ice ridges. As discussed above in connection with ice, the age of the ice gouges and the rate of gouge production remains to be determined in most Arctic offshore areas. Because ice gouges represent a hazard to subsea pipelines, investigations should establish the annual rate of gouge production and determine the in-situ mechanical properties of the reworked sediments.

Soil Properties and Distribution

General knowledge of near-surface marine soils and their distribution in each lease area makes possible the identification of potential geotechnical hazards, as well as the initial screening of candidate platform and pipeline designs. Marine geophysical surveys with shallow soil samples are conducted for each lease area, and hazard maps are developed from these surveys.

Mechanical Properties

Little is known about the mechanical properties of frozen and partially-frozen marine soils under different types of loading conditions, such as dynamic and cyclic loads. Unfrozen soils are generally strong under single or seldom-repeated dynamic loads; but they weaken under cyclic loads. It is not known if frozen marine soils follow the same behavioral pattern. Similarly, the long-term deformational characteristics of frozen and partially-frozen soils are poorly understood. A fundamental laboratory study of the strengths and deformational characteristics of frozen and partially frozen soils under static, sustained, dynamic, and cyclic loadings is needed to provide a general understanding of frozen soil behavior. Additional site-specific studies will be conducted for final structure and pipeline designs.

The problems with frozen soils increase appreciably, in general, if those soils thaw. Mechanical and hydraulic properties, such as strength, compressibility, and permeability of thawed soils (in-situ), as well as the behavior of frozen soils during the thawing process, are not well-defined. In the thawing process, soils may undergo a nonhydraulic consolidation due to the volume change of the pore water. The amount of such consolidation probably depends on temperature, porewater salinity, and mechanical properties and mineralogy of the soil constituents. Again, a fundamental laboratory study, with field data corroboration, of the properties of frozen soils during and after thaw, is needed.

The present-day practices of boring, sampling, depressuring, and subsequently testing marine soil samples may yield unreliable estimates of true in-situ soil strengths, compressibilities, and permeabilities, but yields satisfactory water content, grain-size distributions, and Atterberg limits. Testing of samples from pressurized core barrels are limited to about 300 to 400 ft total depth if subsequent laboratory testing is done in a hyperbaric chamber so that samples are not depressured. Uncertainties in such procedures could be reduced appreciably if the soil properties were measured, in-situ. An alternative method is the development of a simple but reliable wire-line tool to measure in-situ mechanical properties including pore pressure, strength, strength angle, permeability and compressibility.

Shallow coring, accompanied by downhole devices to test soil strength, thermal gradient and acoustic properties, is needed.

C. Earthquakes and Faults

Seismicity

The basic input to an earthquake analysis is a thorough and detailed knowledge of the characteristics of all credible causative faults. The fault characteristics needed are location, length, orientation, geologic slip rate, total slip, activity, and mechanism. A dense seismograph net throughout the Arctic region, both onshore and offshore, makes it possible to establish these characteristics.

Ground Motion

Recent terrestrial observations of structural performance have shown that the ground motions to which a structure responds are different from the ground motions recorded by an instrument in the free field at the same site. The motions to which a structure responds are quite development-specific, depending on site conditions and structure characteristics. At present, ground motions at a particular site are estimated by referring to measured motion at other similar sites. These ground motions are then input to an analytical procedure to calculate the forces in the structure. An analytical procedure should be developed, which is firmly based on physical principles, for calculating the effective ground motions, for a specific site and structure situation, given the instrumentally-recorded ground motions.

It is presently assumed that earthquake ground motions at offshore sites will have the same characteristics as ground motions at onshore sites. A net of onshore and offshore seismographs, including measurements of seafloor ground motion, is needed to establish the validity of this assumption.

D. Design Problems

Pipeline Routing

Regional and site-specific marine surveys should be made to obtain data sufficient for general pipe routing. Bottom stability, shore approaches and crossings, bottom topography, currents and waves, surface faults and near-surface permafrost are among the principal hazards which should be mapped.

Pipeline routes are presently surveyed on a regional basis by geophysical techniques. The recent development of a rapid, inexpensive method to augment geophysical surveys and furnish estimates of the strengths of near-surface soils has been and will be very useful. Improvements in the technology of free-fall penetrators has been a step in this direction.

Pipeline Construction

Warm oil seafloor pipelines over shallow ice-bonded subsea permafrost may present construction and operational problems. A principal construction problem is the burial of the pipe into frozen permafrost soils. Anchoring a pipe-laying barge on near-surface permafrost may prove difficult in some Arctic locations. Burial techniques in offshore near-surface permafrost, in permafrost at shore crossings, and in discontinuous offshore permafrost should be developed.

Warm oil flowlines in close proximity to frozen permafrost may be subject to differential settlement and stresses due to thawing and subsidence. The extent of this problem, and possible design solutions, should be studied for offshore areas where near-surface ice-bonded permafrost is likely to be found.

E. Production Platforms

Pile Supported - Thermal Effects

Piles may be considered either alone or with surface-bearing foundation elements for platforms in certain ice-covered waters. Axial and lateral bearing capacities could potentially be enhanced by freezing the soil around these piles. This possibility should be studied. Behavior under static, cyclic, sustained and dynamic loads should be evaluated as well as the cost effectiveness of this type of foundation element. Analytical, laboratory and field studies may be required in this evaluation.

Gravity Structures

The performance of the foundations, both static and dynamic, for structures in the North Sea has confirmed the validity of current state-of-the-art geotechnical analytical methods. These include evaluation of the non-linear response of the soils to the wave forces and the effects of cumulative strain under repeated cyclic loading on over-consolidated clays. Local scour due to wave-induced currents has occurred in one instance at the corners of a rectangular base caisson founded in sand. Similar geotechnical considerations may pertain to gravity structures in the Arctic offshore. However, lateral forces of ice and waves may impose cyclic loading of greater amplitude and different frequency than those loadings experienced in the North Sea. Shallow-water storm currents in the Bering Sea could exceed North Sea conditions. Magnitude and frequency of bearing loads will depend on ice movement and failure modes, structural stiffness, and soil stiffness. Analytical and model studies will be required to evaluate possible bearing problems for these gravity structures. Another prominent uncertainty relating to the successful deployment of gravity structures for the Arctic relates to the load transfer of global and local ice forces, and how to design structural members to resist them.

The potential for frost heave and thaw settlement exists beneath large gravity structures due to thermal and pressure changes in the marine soils. These thermal and pressure conditions should be studied by analytical modeling and possibly scale-model testing. Specifically, it is recommended that both theoretical and experimental frost heave research on marine soils be initiated together with laboratory testing of the soil types and conditions at representative Arctic marine locations.

Islands

Increased lateral capacity of gravel islands or gravity structures can be obtained by freezing the near-surface marine sediments. Strength and deformational properties of frozen marine sediments should be measured so that the advantages of this approach can be quantified.

Protection of the slopes of gravel islands in the Arctic offshore will be unique because these islands will be exposed to both wave-current and ice forces. In addition, the remoteness of these areas and lack of readily available rip-rap material causes the cost of protection to escalate. Design studies, model testing, and field experience will be required to determine the most cost-effective slope protection.

Gravel islands will be subjected to ice loadings. Facilities will be placed on and in the interior of these islands. Cyclic freezing and thawing adjacent to these facilities will load these structures. Analytical models to predict the deformation and strength of these islands have been developed; however, research should continue to investigate strength and stress-strain properties of frozen island fill and marine soils.

Impact on Coastal Processes

For those offshore lease areas that are near the coast, gravel islands connected with gravel causeways are a possibility in shallow water (at depths less than 30 ft.) This approach would provide continuous all-weather equipment access to production locations as well as support for and more easily-maintained pipelines and power cables. The impact of such causeways and production islands on coastal sedimentary processes, on the interruption of ice movement, and their consequences, should be studied. Special sensitivities have been attached to development of Arctic coastal areas. These sensitivities involve the interaction of ecological, geological and physical factors. For example, the construction of islands in shallow bays to support exploration or production facilities, the creation of causeways for transportation of gravel during island construction, and the use of causeways as pipeline routes to shore, may affect the ecological balance of the bay-lagoon systems. The ecological consequences of such construction processes have been studied to a limited extent in the Arctic Outer Continental Shelf Environmental Assessment Program, but further investigations are needed. Sedimentation patterns are governed by alluvial material entering the shore and its redistribution by littoral currents. In lagoons and bays, tidal currents also redistribute material, much of which is organic. Natural systems of this type are not static, as excess flood waters or strong coastal waves and currents increase deposition or erosion. Construction in bays will change the dynamics of tidal flow, altering shore erosion, and indirectly affecting ice ride-up on beaches. The Arctic barrier islands are not stable, and fixed construction sites may interact with their rate of formation and movement. Model-scale hydraulic studies may shed light on the options available. Among thermal effects, coastal flooding should be considered. Because of the differences in time of thaw on land and offshore, spring melt-water descends over the still-frozen ice of the bays and coastal areas. The warmer waters create special thermal erosion along the coast. Modeling of such effects for control of possible consequences may be feasible.

F. Deep Soils

Distribution of Soils With Depth; Areal Extent

Stratigraphy, origin and special problems associated with sediments at depth are of importance in the Arctic offshore. Basic information is usually obtained by seismic profiling, deep coring, well logging, and extrapolation from onshore stratigraphic information.

The geologic history (i.e., stratigraphic sequence) of the sub-surface at depths governed by Pleistocene or younger deposition has unique attributes in the Arctic. Glaciation, coupled with lower sea levels in the five ice ages, not only influenced the type of materials deposited (namely unsorted glacial outwash and morainal units), but extended the permafrost to the shelf which is now offshore. Knowledge of the depositional history in areas of development is important for foundation design and casing studies. Small changes in soil composition may bear heavily on the distribution of permafrost, on the possible occurrence of hydrates and the inclusion of ground water.

Thermal history of sediments at depth is one controlling element in the distribution of ice-bonded sediments. To help determine this, downhole temperature measurements of the permafrost are very useful.

Offshore relict permafrost is relatively warm, usually in the range of two or three degrees Celsius below freezing. It is in non-equilibrium, thermally, with heat flow from the earth, and is in the process of thawing from the top downwards and from the bottom upwards. Based primarily on drilling experience to date in the Canadian Beaufort Sea, subsea permafrost has been encountered at significant depths. Depending on soil type and salinity, offshore permafrost may be discontinuous with depth. A better understanding of permafrost conditions will be required for final structural design, well completion design, well spacing determination, and pipeline design. However, the data will be needed on a site-specific basis following a commercial discovery. It is important to know the depth to the upper and lower boundaries of the permafrost as a function of distance from shore and water depth; and to what extent offshore permafrost is discontinuous with depth. To answer these questions, a field instrumentation and sampling program must be employed.

Hydrates

Although naturally-occurring hydrates have not been encountered at Prudhoe Bay, hydrate evidence during drilling has been obtained in the Mackenzie Delta, Arctic Islands, Canadian Beaufort Sea and west of Prudhoe Bay. Because of potential problems caused by thermal decomposition of hydrates during drilling and production, hydrate intervals must be detected and properly cased. As in the case of permafrost, the need for hydrate location data will be site-specific. As part of the permafrost program recommended above, it is suggested that hydrate detection also be included. Because of the present lack of technical knowledge of in-situ hydrates, a program on hydrate detection and evalua-

tion should be initiated, with emphasis on development of sensing and sampling tools.

Because of the presently-inferred impermeability of permafrost, the potential exists for abnormally pressured gas that is trapped within or below permafrost. Such zones should be recognized and detected as part of any drilling and deep coring program.

G. Deep Soils - Earthquakes and Faults

Ground Motion at Depth

In principle, the earthquake ground motions at depth (e.g., a wavelength or so) should be less than the surface ground motions. Almost all of the available data on earthquake ground motion comes from surface-based instruments. A study of the seismological literature, the literature on underground nuclear testing, and the installation of a few deep accelerographs adjacent to surface accelerographs could resolve this question.

Fault Displacement

Well casings have been severed by fault creep in non-earthquake areas and by sudden movements along faults in earthquake areas. It is, in principle, possible to protect against such damage. This requires a knowledge of 1) the slip rate along the fault, 2) the magnitude of movements during an earthquake, and 3) the location of the fault plane. These problems have been encountered in other OCS areas where exploration and development have occurred. Faults in proposed lease areas need to be identified and an assessment made of their characteristics. Known active faults may thus be avoided during drilling. Design measures which may be taken to minimize the possibility of damage to the well casing also should be considered.

H. Hydrate Considerations for Production Wells

Casing Loads

If in-situ hydrates are present in the Arctic offshore regions, the hydrate intervals will "thaw" or decompose around the wellbore due to heat transfer from warm production fluids. Upon decomposition, the released gas can generate significant pressure on the well casing. Knowledge of maximum pressures must be known for casing design to prevent collapse, unless another approach (pressure relief) is utilized. The pressure buildup due to hydrate decomposition is a function of many variables, including mechanical and strength properties of the hydrate formation. Analytical studies, laboratory investigations, and field testing will be needed to solve the hydrate loading problem. Studies should include: 1) the possibility of hydrofracturing; 2) resolution of gases in the surrounding unfrozen pore fluids; 3) permeability of frozen soils relative to gas flow; 4) movement of gas through partially or fully saturated, frozen or partially frozen soils.

Cementing

Cement interaction with in-situ hydrates must be understood in order to properly cement well casing within hydrate intervals. Thermally-generated gas evolved from hydrate sources during placement and setting of cement may permeate the cement slurry, causing a reduction in cement strength and creating permeable paths with loss of sealing capability. Even with a wellbore drilled with chilled mud, heat of hydration released by the cement as it sets may cause hydrate gas evolution around the cement sheath. A laboratory testing program is recommended for improved cement systems for application to in-situ hydrates.

IV. INSTRUMENTATION DEVELOPMENT

New and advanced diagnostic techniques will be required in the frontier areas of Alaskan oil and gas production. These new diagnostic techniques must operate in the severe environment of the Arctic offshore, in remote locations with quite different data recording and storage capabilities. Existing sensors and technologies will be used where applicable, and the integration of new diagnostics in the present system will be accomplished as needed. The following categories have been identified as primary areas where diagnostic instrumentation is required.

Electrical Properties of Ice

There is considerable interest in developing an instrument to accurately measure ice thickness for both research and reconnaissance logistics during operations. While several instruments have been developed and tested, improved performance over ice of variable salinities is needed, as well as increased depth penetration. Generally, promising instruments are electrical in nature and the varying dielectric properties of ice affect the measurement. It seems apparent that more information regarding the dielectric properties of sea ice is desired to not only guide instrument development but to increase confidence in the measurement provided by the instrument itself. Improved understanding of the electromagnetic properties of sea ice and snow would also improve remote sensing interpretation.

Ice Property Measurements

The mechanical and physical properties of the many varying types of ice in the Arctic need to be measured, both in-situ and in the laboratory. The in-situ properties that are important include in-situ stresses, stress-strain relationships, shear strength, tensile strength, compressive strength, crack distribution, and other properties, as well as the physical properties of temperature, salinity, density, and consolidation. The correlation of these properties as determined in-situ, with laboratory measurements, needs to be verified.

Ice Ridge Properties

Sheet ice, as it is forced by winds and waves, deforms and creates ice ridges. After formation, these ridges may change shape and size with time, with concomitant strength and salinity changes. Ridge properties that are of importance include, among other things, the bonding and amount of consolidation of the ice blocks, the salinity of the ice, and the strength profile throughout the ridge. Instrumentation to determine ridge profile above and below the water line is also of importance.

Ice Location

The three categories of sheet ice, ice ridges, and ice islands are important for determining ice forces. The location of these types of ice versus time, and amount of ice coverage, needs to be determined. Tracking information would contain velocities and locations versus the ice forming seasons and would be used for predicting ice coverage and locations. The statistical data on ice locations would be used for modeling the structural designs and design philosophies.

Ice Interactions with Operational Structures

Interaction of all types of ice with gravel islands, production structures, ice-breaking ships, and subsurface pipe lines are important. The development of this category of diagnostic instrumentation would be dependent upon ice properties, ice motions, and structural design loads. Diagnostic instrumentation requirements could include systems for measurement of pipeline integrity, motions and deformations. Shipboard and structural instrumentation probably exists within the current state-of-the-art for diagnosis of these conditions. Instrumentation has been developed to monitor gravel islands subject to impinging ice, but both advanced diagnostic instrumentation and inexpensive warning devices may be appropriate.

In-Situ Soil Properties

The in-situ soil properties at the water-mudline interface, as well as at depth, require instrumentation. Seafloor measurements that may be required include acceleration loads created by earthquakes, soil shear strength profiles, and possibly other soil parameters. Deep soil properties of interest include permafrost regions, and possible hydrate regions. Both of these regions will have problems associated with drilling and completions, caused by their reaction with drilling fluids and change of temperature with time. The diagnostic instrumentation for determining location and physical properties of permafrost and hydrates will require new advanced instrumentation systems.

Other

Several other instrumentation systems may be required to meet future needs of the Arctic fossil energy program. These may include

further development of remote meteorological stations for deployment in pack ice. A weather station in the Navarin Basin may be needed. Another possible surveillance system may be a tethered system for allowing ice-breaking ships or tanker ships to view the ice pack for several tens of miles ahead of their location. Another system that can be envisioned would be an ice tracking system that was permanently mounted on the seafloor around production structures in deeper water, to give advance real-time warning of large ice motions toward the structure, and to provide opportunities for ice-structure interaction measurements.

The instrumentation in the Arctic environment will obviously evolve into new areas, as new diagnostic requirements are uncovered. These new areas cannot presently be foreseen but, as in any program where information is gathered, the amount of data required will increase as definition of the problems becomes more specific in each of these areas.

RESEARCH PROJECT TASKS

1. Verify hindcast models for Arctic areas that include the influence of ice cover on wave and surge generation, and shallow water effects.
2. Investigate methods to date ice gouges of the seafloor.
3. Investigate mechanics of ice gouging as a function of sediment type.
4. Conduct confined and unconfined tests to provide data on strength and stress/strain behavior of sea ice and freshwater ice as a function of environmental parameters and loading rates.
5. Conduct in-situ beam tests to obtain flexural strength data.
6. Conduct large scale and small scale tests on the same sea ice to investigate size effects.
7. Investigate analytical procedures to predict size effects.
8. Obtain data on dielectric and electromagnetic properties of sea ice.
9. Obtain engineering data on frictional forces between ice and other materials.
10. Obtain data on adhesion bond strength.
11. Collect in-situ measurements of first-year and multiyear ridge geometry and properties.
12. Measure ice drift velocity.
13. Develop and verify regional ice dynamics models.
14. Conduct systematic stereo photography, laser overflights, and sonar measurement programs to obtain ridge profile distributions.
15. Verify use of passive microwave imagery to identify multiyear ice.
16. Process available satellite imagery to provide data on multiyear ice movement and floe size distribution.
17. Develop physical model of pack ice edge movement.
18. Compile pack ice edge data to verify the ice edge movement model.

19. Obtain field measurements of ice state, e.g., crystal structure, composition, temperature, and snow cover.
20. Utilize ships of opportunity and specific icebreaker voyages to collect data on ice conditions.
21. Conduct oceanographic/meteorological measurement program.
22. Conduct systematic side-scan sonar and bathymetric surveys in the Beaufort Sea to water depths of 80 m and in the Chukchi Sea.
23. Sponsor a logistics base at the Naval Arctic Research Laboratory, Barrow, and an equivalent operating base at Nome to conduct field studies in the Chukchi and Bering Seas.
24. Improve understanding of failure modes of a variety of ice features against various types of structures.
25. Investigate the influence of random flaws and nonsimultaneous structure contact on total ice forces.
26. Develop a model of driving force and average ridge-building forces across a wider structure front.
27. Describe local ice pressures as a function of ice mechanical properties, ice velocity, and contact geometry.
28. Investigate the characteristics and effects of rubble fields around structures.
29. Consider test structure verification of ice/structure interaction models.
30. Conduct model tests and develop predictive theories for ice rideup on islands and structures.
31. Develop improved techniques to predict wave runup and overtopping.
32. Investigate non-linear surface effects for wave diffraction theory.
33. Evaluate impact loads upon structures from storm-driven ice floes.
34. Conduct studies to investigate ice actions on slope protection systems.
35. Improve prediction of ice ridge penetration resistance for ice-breakers.
36. Develop models of ship/multi-year ice ridge breaching.
37. Develop model to predict ice pressure-induced delays in ship transit.

38. Develop a verified model for high energy penetration, resistance, and pressure on a ship's hull pursuant to collision with an ice feature.
39. Accelerate development of models to predict ice forces on propellers and conduct full scale verification trials.
40. Conduct full scale and model tests to improve propulsion efficiency in ice.
41. Extend existing models of ship/terminal interactions in ice to more severe ice conditions of the Arctic offshore. Verify with model tests.
42. Develop mathematical models and physical modeling techniques to improve ship maneuvering performance in ice.
43. Develop models to predict variations in ship performance in level ice due to changes in ice strength, hull shape, and snow cover.
44. The characterization of the sea floor should be completed in the regions of the Arctic offshore which will be subject to petroleum development.
45. The mechanical properties of sediments on the sea bed should be determined.
46. Geomorphological processes acting upon the seafloor, such as ice scour, must be described more precisely.
47. The ground motion offshore which results from earthquakes should be measured.
48. A model of thaw and subsidence for a warm subsea pipeline buried in offshore permafrost should be developed.
49. Frost heave in marine soils and gravels containing seawater deserves further investigation.
50. The procedures for predicting behavior of pilings and island foundations installed above subsea permafrost should be refined.
51. Effects of artificial islands and causeways upon natural coastal processes should continue to be studied.
52. The location and extent of ice-bonded subsea permafrost should be determined for the Arctic offshore basins which are expected to be developed.
53. A remote sensing technique for detection of gas hydrates, in-situ, should be perfected.

54. The location of active subsurface faults should be determined.
55. Both theoretical and remote-sensing techniques should be applied to ascertain the extent of thaw of gas hydrates during production, and the possible resulting subsidence.
56. The technology of cementing casing in regions where gas hydrates have been penetrated should be perfected.
57. Instrumentation for both laboratory and in-situ measurements of ice properties should be reviewed and perfected.
58. Methods should be developed for rapid and easy assessment of ice ridge profiles and degree of consolidation.
59. Diagnostic instrumentation should be developed to measure the interaction of ice with prototype or operational artificial islands, structures, and subsea pipelines.
60. An advanced ice surveillance system to be used in an operational mode for ship routing in ice-infested waters should be designed.