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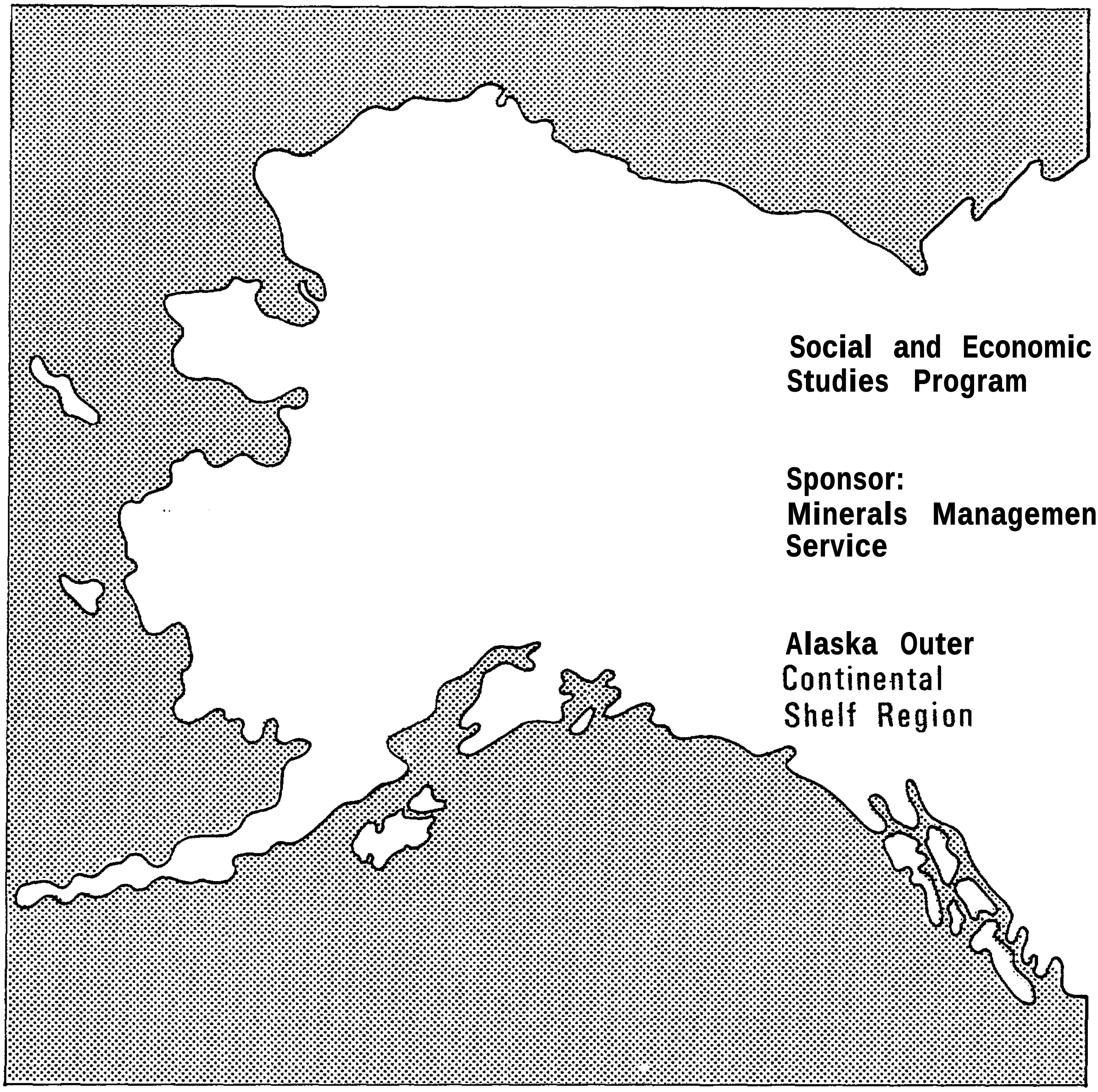

**Social and Economic Studies Program**

**Sponsor:**
**Minerals Management Service**

**Alaska Outer Continental Shelf Region**

# Beaufort Sea Petroleum Technology Assessment

TECHNICAL REPORT NO. 112 CONTRACT NO. 14-12-0001-30154

# BEAUFORT SEA
# PETROLEUM TECHNOLOGY ASSESSMENT

Prepared For:

MINERALS MANAGEMENT SERVICE

ALASKA OUTER CONTINENTAL SHELF REGION

LEASING AND ENVIRONMENT OFFICE

SOCIAL AND ECONOMIC STUDIES UNIT

Prepared By

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NEW YORK, NEW YORK

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# NOTICE

# BEAUFORT SEA
# PETROLEUM TECHNOLOGY ASSESSMENT

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# BEAUFORT SEA PETROLEUM TECHNOLOGY ASSESSMENT

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# ABSTRACT

The objectives of this study are to assess the present state of petroleum technology in the region of the Diapir Field Sale 97 and to analyze the unit costs, construction schedules, and manpower requirements associated with offshore petroleum development. Values for all relevant environmental parameters are established and the forces exerted on offshore structures are determined based on information available in the public domain. Assumed petroleum production parameters and potential sources of onshore and offshore granular borrow material are defined. The construction techniques unique to offshore development in the Beaufort Sea, along with relevant unit costs, are presented, including sand and gravel extraction and utilization, dredges and dredging, towing large offshore structures, and structure concept and prefabrication techniques. The weight and space requirements and cost of exploration and production topsides equipment are developed. Drilling techniques and costs for exploration and development wells are described as are ancillary vessel technology, manpower requirements and costs. Offshore operations in the study area will require onshore support facilities and base camp requirements and costs are described.

A number of exploration platform concepts have been proposed and there exists no absolute engineering constraint to the development of these concepts. In order to estimate exploration platform costs, and ultimately exploration well drilling costs, generalized platform concepts are developed for Artificial Island, Bottom Founded and Floating

exploration systems. In water depths greater than approximately 35 m (115 ft) prefabricated bottom founded structures are the most cost effective exploration platforms, while in shallower waters caisson retained islands and sacrificial beach islands may be more cost effective, depending on the location of a suitable source of granular fill.

As for exploration platforms, there exists no absolute engineering constraint to the development of production platforms in the study area, but their cost will be considerably greater due to the requirement to stay on station for a long period of time and the need to support oil/gas/water separation equipment. Prefabricated bottom founded structures are the most cost effective production platforms in all but the shallowest study area water depths, and then only if suitable granular borrow material can be dredged from a source adjacent to the site, in which case a caisson retained island may be preferred.

The primary alternative for transporting crude oil from the study area is to install a marine pipeline to shore and a land pipeline connecting to the existing Trans-Alaska Pipeline System (TAPS). As a sensitivity case analysis it is assumed that TAPS will be unavailable and a number of alternative transportation systems are considered. An assessment of the technology, manpower requirements and costs for the major elements of the various transportation system alternatives, including marine pipelines, land pipelines, offshore loading terminals, nearshore loading terminals and Arctic tankers, is presented.

# 1.0 INTRODUCTION

## 1.1 OBJECTIVES

The objectives of this study are to assess the present state of petroleum technology in the region of the Diapir Field Sale 97 (December, 1986) and to analyze the unit costs, construction schedules, and manpower requirements associated with offshore petroleum development. The development technologies to be evaluated specifically include exploration, production and transportation of crude oil reserves from the multi-year ice zone of the Beaufort Sea. Survey activity required prior to exploration drilling is not included. At the direction of the Minerals Management Service, the production of non-associated natural gas is also excluded because such production from the study region will probably not be economically feasible for at least twenty years.

The specific objectives of this study are:

- to identify and evaluate the various technologies associated with offshore petroleum development in the multi-year ice zone of the Beaufort Sea.
- to analyze in detail the potential for the extraction and use of onshore and offshore sand and gravel resources for exploration and production platforms, causeways, etc.
- To analyze the unit costs, timing, and manpower

associated with offshore petroleum development in the Beaufort Sea.

Petroleum technology, in conjunction with regulatory considerations, will influence or determine:

- scheduling of offshore and onshore activities,
- local employment and infrastructure support requirements, and
- potential risks involved in the production and transportation of hydrocarbons.

Thus, this petroleum technology assessment provides a key part of the information necessary to assess the environmental and socioeconomic impacts of petroleum development in the Diapir Field planning area. It provides part of the framework for the Minerals Management Service to estimate the resource potential, prepare Environmental Impact Statements, and to assess the potential social, economic and physical effects of petroleum development in the Beaufort Sea.

## 1.2 STUDY AREA

The area considered in this study includes the region within the Diapir Field Planning Area where water depths range from 20 to 90 m (65 to 300 ft). The 20 m (65 ft) lower boundary has been selected because it is the limit of current activity in the Alaskan Beaufort Sea. The exploration, production and transportation technologies required for the study area are those which will be required for the region to be included in Lease Sale 97, scheduled for August 1986. A general location map of the Diapir Field is shown in Figure 1.2-1.

For purposes of establishing environmental and geotechnical parameters upon which to base the technological assessment, the Diapir Field Planning Area has been divided into three sectors designated as the Western, Central and Eastern sectors. The study region is shown in Figure 1.2-2. The Western sector is bounded on the north by 73 north latitude, on the east by 155 west longitude, on the southeast by the Alaskan mainland, on the southwest by 71 north latitude, and on the west by 162 west longitude. The Central sector is bounded on the north by 73 north latitude, on the east by 146 west longitude, on the south by the Alaskan mainland, and on the west by 155 west longitude. The Eastern sector is bounded on the north (western portion) by 73 north latitude, on the east (northern portion) by 141 west longitude, on the north (eastern portion) by 72 north latitude, on the east (southern portion) by the U.S.-Canadian fishery conservation line, on the south by the Alaskan mainland, and

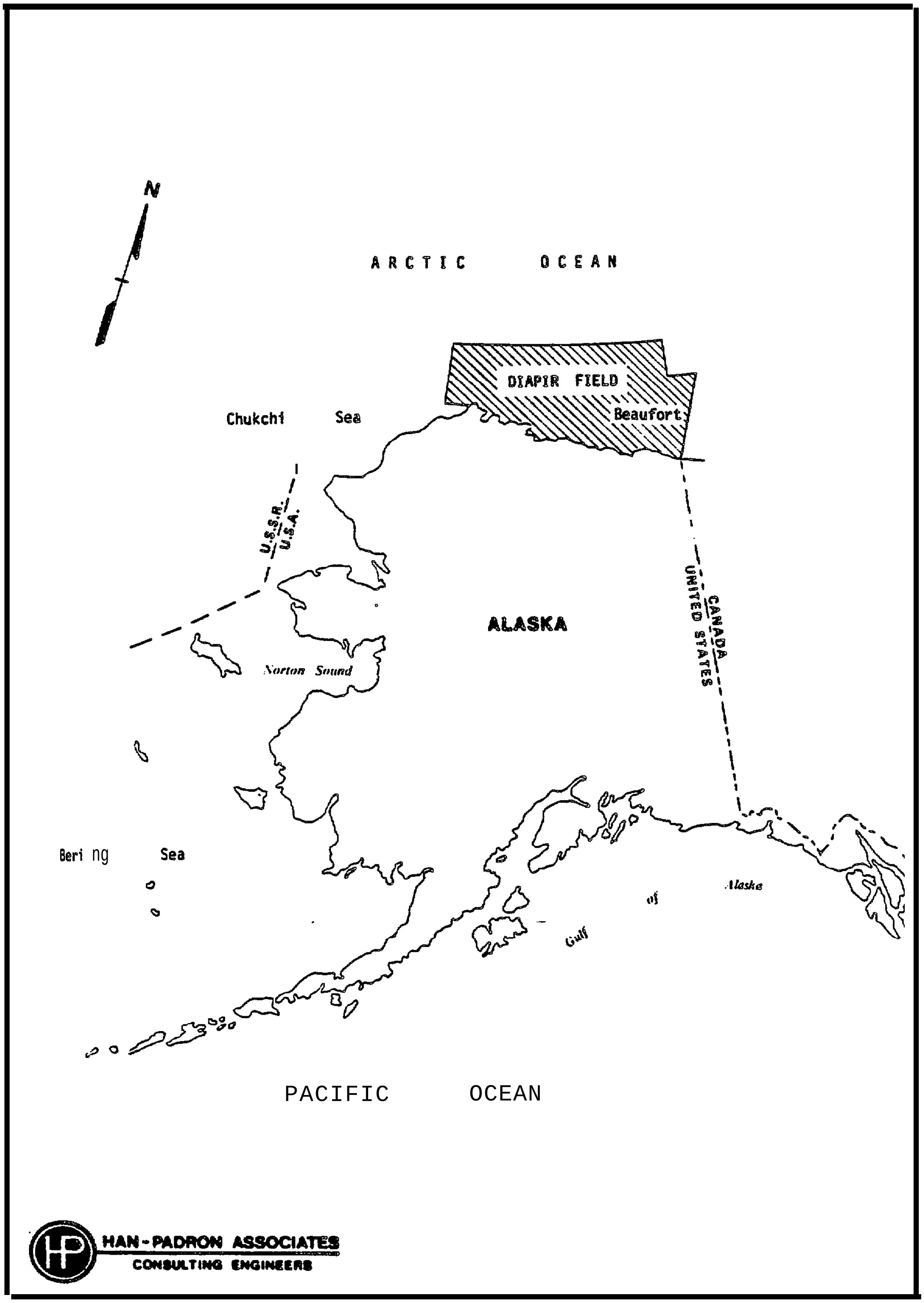


Figure **1.2-1. Diapir Field general** location map.

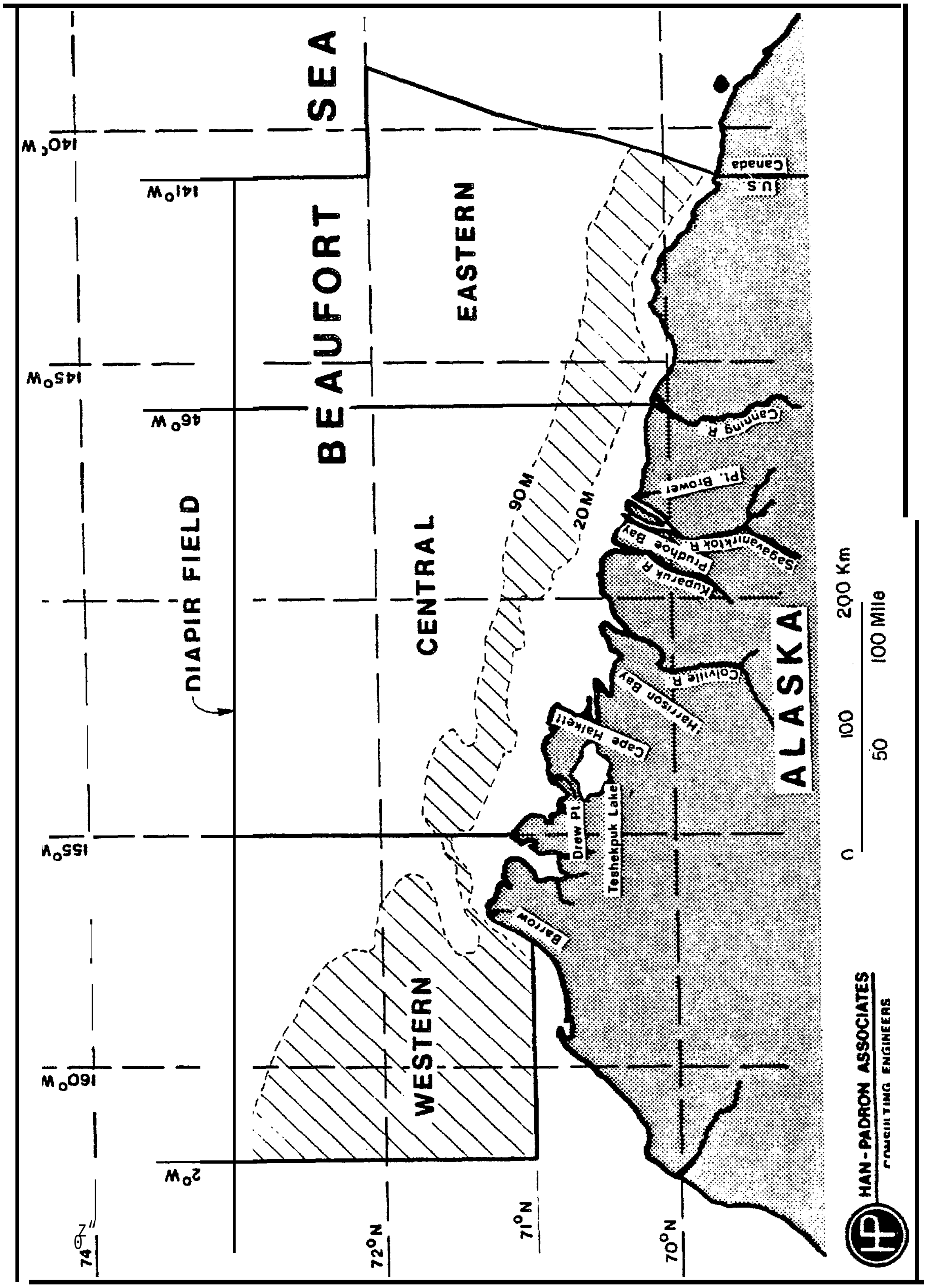


Figure 1.2-2. **Beaufort** Sea petroleum technology assessment study area.

on the west by 146 west longitude. The study areas within each sector are bounded, as stated previously, on the north by the 90 m (300 ft) isobath and on the south by the 20 m (65 ft ) isobath.

## 1.3 PROCEDURE

Petroleum development can be categorized into three major activities, i.e. , exploration, production and transportation. The primary objective of this study is to organize and update the existing data base of potential technologies and development costs for these major activities in the Beaufort Sea study region. In order to evaluate the technological and economic feasibility of the various components of the petroleum exploration, production and transportation scenarios, a number of technological and cost assumptions have been made. In addition, specific design values for environmental parameters, petroleum production parameters’and quantity, quality and location of sand and gravel resources were established.

The procedure used in carrying out the petroleum technology assessment is in accordance with the following sequence:

- Extensive research and evaluation of available information regarding the study area environment was carried out. This work was used to establish specific design values for the environmental parameters that affect the design and operation of petroleum development facilities. The analyses carried out were based upon environmental data available in the public domain. There are additional environmental data existent but they are proprietary and not available for this study. While the available data are quite extensive and are adequate for purposes of this study, they are not sufficient to provide a sound basis for the final selection and design of the facilities required for a particular scenario. The cost of many of the petroleum development elements are quite sensitive to specific site conditions and such conditions must be fully defined before a final analysis and design can be performed.

- Based on the defined environmental parameters, the forces acting on offshore structures in the study area were determined. The forces exerted by ice were based on an evaluation of the various research and procedures described in the latest literature available in the public domain.

- Petroleum production parameters on which the technology assessment is based were established jointly with Minerals Management Service.

- The technology, manpower requirements, capital costs and operating costs of petroleum development activities that are related to a number of different exploration, production and/or transportation concepts were developed to serve as "building blocks" for the overall petroleum technology assessment.

- A thorough search of recent literature, as well as communication with developers, promoters and actual and potential industry users of existing and proposed exploration and production platforms, was conducted.

- The various existing and proposed concepts were reviewed and generalized concepts for various categories of exploration and production platforms were developed. The generalized concepts take into account the influencing factors and constraints affecting the suitability of each concept. These influencing factors and constraints include environmental factors, construction considerations, operational constraints and technology availability. Environmental factors include ice conditions, waves, water depth, winds, currents, tides/storm surge, geotechnical conditions, geology and geologic hazards and meteorological conditions. Construction constraints include fabrication requirements, transportation requirements and installation procedures. Operational constraints include space and weight requirements for exploration and production equipment, logistics of supplying and supporting exploration and production operations, maintenance requirements, personnel safety considerations and potential hazard to the environment. Technology availability refers to the need to develop new technology as opposed to utilizing or modifying existing technology.

- Per well drilling costs for the various exploration platform concepts were developed and utilized to determine the most cost effective generalized exploration system for all study area water depths.

- Total capital costs for the various production platform concepts were developed and utilized to determine the most cost effective generalized production platform for all study area water depths.

- The technology, manpower requirements and costs for the major elements of the various transportation system alternatives were evaluated, including marine pipelines, land pipelines, offshore loading terminals, nearshore loading terminals and Arctic tankers.

- For illustrative purposes, two representative petroleum development scenarios were defined and an analysis conducted to select the optimum transportation system and determine the production and transportation costs.

All costs presented in this report are based on constant, January 1982 U.S. dollars and do not account for future inflation. All present value calculations were based on an 8 percent rate of return and the effect of taxes and royalties, although of great significance in the economic viability of a potential development project, were not considered in this study. No allowance has been made for delays and consequent cost escalation that may result from permit and regulatory difficulties which again may be of great significance. Experience has shown that permitting, especially in environmentally sensitive areas, is invariably on the critical path and often has a major effect on project costs. Construction costs were considered to be expended uniformly over the construction period of each facility.

Study area petroleum development has been analyzed separately, assuming no linking with development elsewhere. Thus, it has been assumed that there will be no sharing of costs of any of the petroleum development elements (pipelines, tankers, terminals, support bases, etc.) except that transportation alternatives consider the use of the existing Trans Alaska Pipeline System (TAPS) and its haul road.

This report provides early information for the Minerals Management Service to initiate planning for Lease Sale 97. As such, this is part of the regulatory process for outer continental shelf development, but specific stipulations regarding this lease sale are not known at this time. Therefore, scheduling assumptions make only general allowance for the permit process and it has been assumed that permits are not the critical path to a field's development. Also the costs associated with the permitting process, which may be quite substantial, have not been considered in this study. It is basically assumed that permits can be successfully obtained simultaneously with other early development steps. This is feasible to a point, but the ultimate commitment of the decision to develop is significantly affected by permitting requirements.

## 1.4 REPORT CONTENT AND FORMAT

This report has been organized, starting with Chapter 3, in the sequence in which an engineering evaluation to determine the optimum petroleum development scenario would be carried out.

Chapter 2 presents a summary of the findings of the study.

Chapter 3 describes the approach, assumptions and reasoning used in establishing the environmental and other design criteria on which the petroleum technology assessment is based. Section 3.1 describes the methodology used to establish design values for each of the environmental criteria and Section 3.2 describes the procedures used to calculate the environmental forces acting on each of the offshore facilities. Section 3.3 defines the characteristics of the crude oil to be produced, the quantity recoverable, the initial productivity and the optimum rate of recovery used for this study. Section 3.4 describes the location, quantity and quality of sand and gravel resources and presents recommendations for priorities in the selection of borrow sources.

Chapter 4 describes the technology, manpower requirements, capital costs, operating costs, etc., of petroleum development activities that are related to a number of different exploration, production and/or transportation concepts. The construction techniques unique to offshore construction in the Beaufort Sea are described and unit costs developed in Section 4.1. Section 4.2 describes the topside facilities provided on exploration and production platforms in the Beaufort Sea and defines topside weight, space requirements, manpower requirements capital cost and operating cost. The technology and cost associated with drilling exploration, delineation and development wells are presented in Section 4.3. The procedures for transporting oil field supplies, drilling/production equipment and other material requirements from ports in the contiguous United States to the Beaufort region are described in Section 4.4. This section also describes the costs and characteristics of icebreaking multi-purpose supply vessels to be utilized in the deeper waters of the Beaufort Sea. Section 4.5 describes each of the elements that make up the onshore support facilities and presents construction and operation manpower and equipment requirements and capital and operating costs.

Chapter 5 presents the technology assessment for exploration activities in the study area. Section 5.1 describes the numerous exploration platform concepts that have been proposed or constructed. For each general classification of exploration platform, Section 5.2 presents preliminary designs and cost estimates. In Section 5.3, total exploration costs are developed and presented on a per well basis as a function of water depth.

Chapter 6 presents the technology assessment for production platforms in the study area. Section 6.1 describes the numerous production platform concepts that have been proposed. For each general classification of production platform, Section 6.2 presents preliminary designs and cost estimates. Section 6.3 presents the development of the minimum production platform costs for the range of production rates and water depths considered.

Chapter 7 provides an assessment of the technology and costs for the major elements of the various transportation system alternatives. Section 7.1 contains a discussion of the factors to be considered in determining the feasibility and designing marine pipelines in the Beaufort Sea and presents unit costs for marine pipelines. Section 7.2 contains a similar discussion for land pipelines. Sections 7.3 and 7.4 contain discussions of the technology and costs of offshore and nearshore loading terminals, respectively. The characteristics, performance and costs of Arctic tankers are described in Section 7.5.

All references are fully documented in Chapter 8.

In the appendix, two scenarios are defined, representative of significantly different petroleum development requirements. All relevant environmental and production parameters are defined for each scenario and simplified analyses of the costs are developed to serve as examples of the uses of this report.

## 2.0 SUMMARY OF FINDINGS

The findings of this study are summarized below. They are based on numerous conditions, criteria and assumptions defined throughout the text of this report. Significant changes in these factors could, of course, change the findings.

- Sea ice presents the major environmental hazard to petroleum development facilities in the Beaufort Sea (Section 3.1.1).

- Sufficient information on sea ice and other environmental criteria is available on which to base preliminary designs but final designs must be based on site specific data and an analysis of the nature of the ice/structure interaction for the structural configurations to be considered (Section 3.1.1).

- Further study to determine the probability and consequences of ice island interaction with a bottom founded production platform is required (Section 3.1.1).

- Exploration and production costs are sensitive to seabed conditions and any offshore project will require an extensive, site-specific, detailed geotechnical program to drill, sample, in-situ test and thermally instrument the subsoils of the proposed site (Section 3.1.7).

- Onshore and offshore sources of granular borrow material have been identified but site-specific field and laboratory studies are required to confirm the quality and quantity of these resources (Section 3.4).

- A number of exploration and production platform concepts have been proposed for the water depths of the study area and there exists no absolute engineering constraint to their development (Section 5.1).

- In water depths greater than approximately 35 m (115 ft) prefabricated bottom founded structures are the most cost effective exploration platforms, while in shallower waters caisson retained islands and sacrificial beach islands may be more cost effective, depending on the location of a suitable source of granular fill relative to the exploration site (Section 5.2).

- Floating exploration platforms, with their limited drilling season resulting from a combination of severe ice conditions and current regulatory constraints for the protection of whales, are not cost effective for extensive drilling programs (Section 5.2).

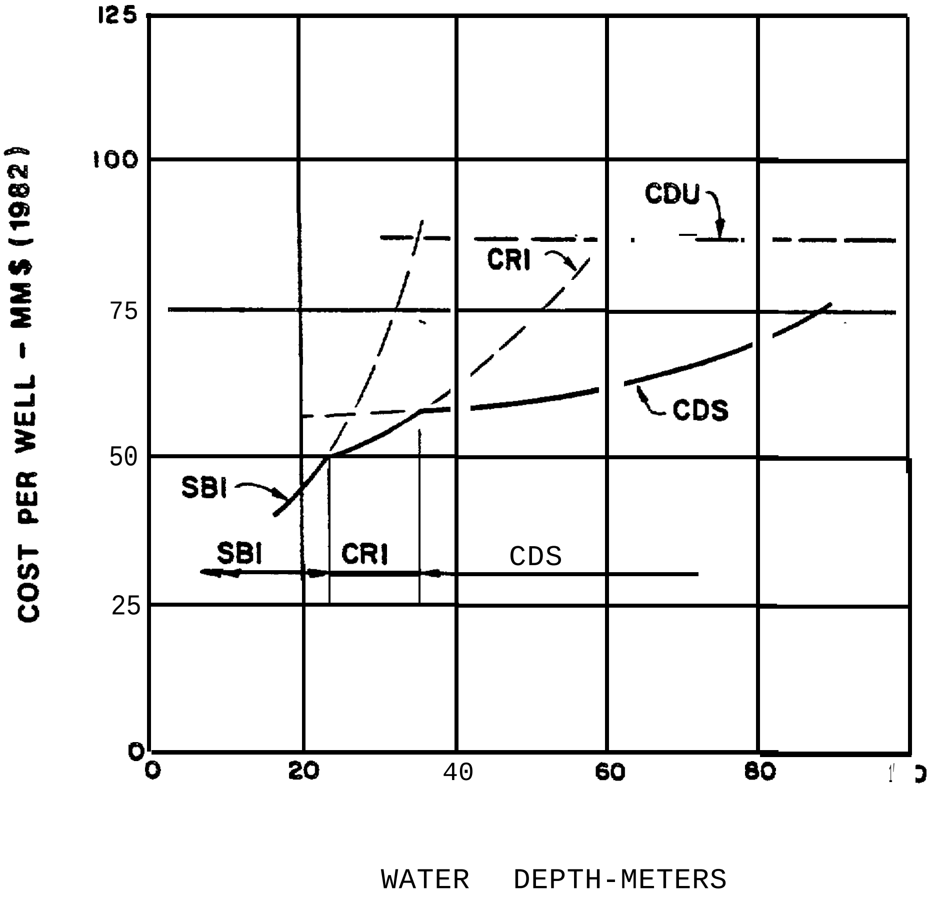
- The approximate cost of drilling a 3,000 m (10,000 ft) deep exploration well in the study area is shown in Figures 2.0-1 and 2.0-2. The dashed lines indicate the cost for each type of exploration platform as a function of water depth and the solid lines indicate the least cost alternative for each water depth (Section 5.3).

- Prefabricated bottom founded structures are the most cost effective production platforms in all but the shallowest study area water depths, and then only if suitable granular borrow material can be dredged from a source adjacent to the site, in which case a caisson retained island may be preferred (Section 6.2).

- The approximate capital cost of a production platform in the study area, including topsides drilling and production equipment, is shown in Figure 2.0-3 (Section 6.3).

- If the Trans-Alaska Pipeline System (TAPS) is available, - it will be utilized for transporting crude oil from the study area (Section 7.0).

- If TAPS is not available, the use of Class 8 icebreaker tankers is the most cost effective crude oil transportation system for the study area for the production rates considered (Appendix).



COST BASED ON 3000M DEEP UELL

S81 - Sacrificial Beach Island
**CRI** - Caisson Retained Island
CDS - Conical Drilling Structure
**CDU** - Conical Drilling Unit (floating)

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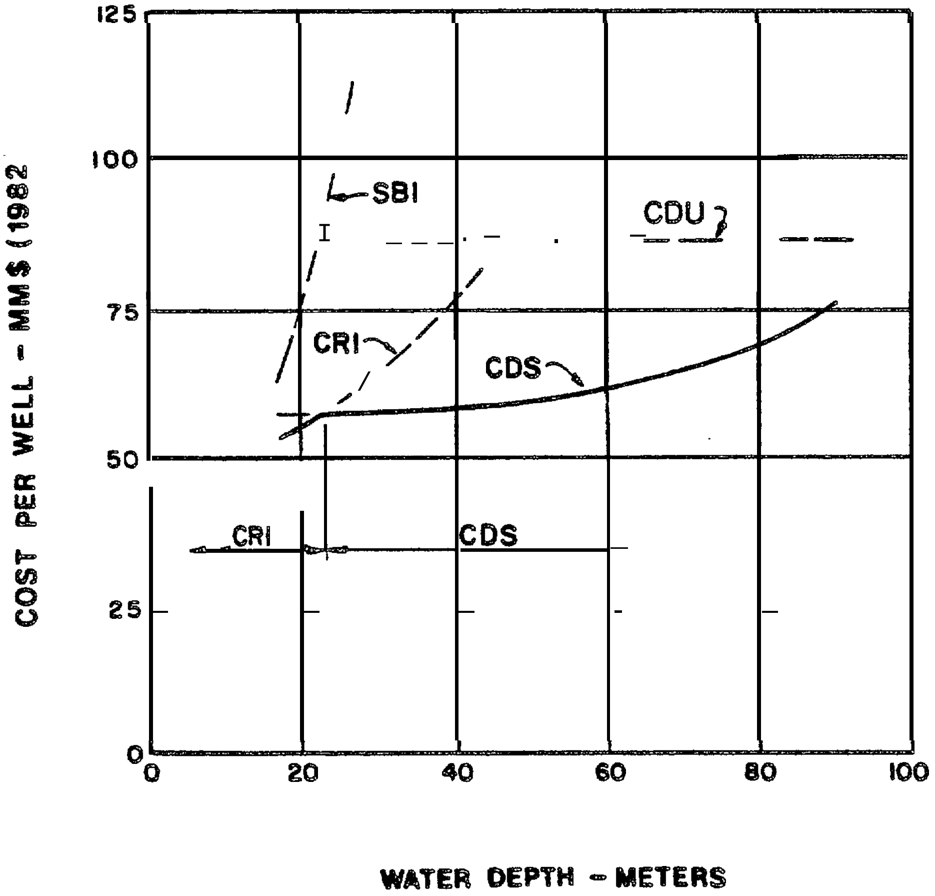
Figure **2.0-1. Per well** cost versus water depth - borrow source at site.



COST BASED ON 3000M DEEP WELL

SBI - Sacrificial Beach Island
CRI - Caisson Retained Island
CDS - Conical hilling Structure
CDU - Conical Drilling Unit (floating)

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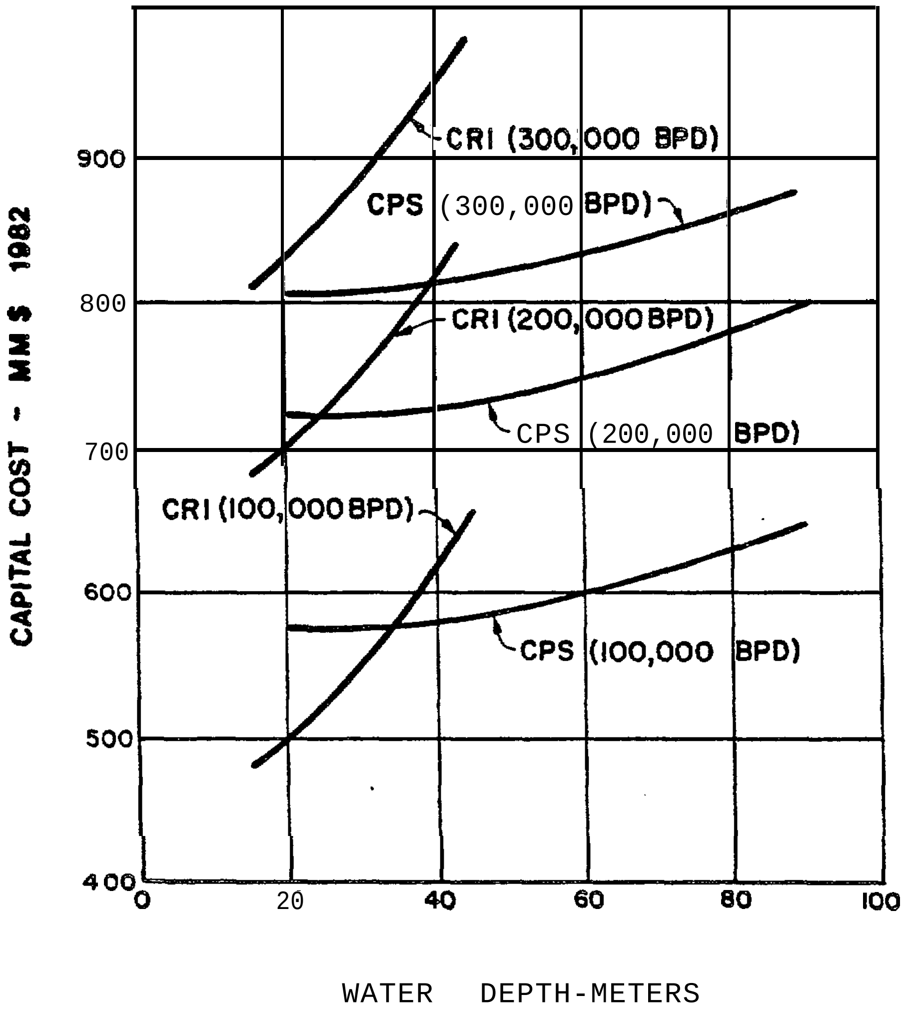
**Figure** 2.0-2. Per well cost versus water depth - borrow source 10 km from site.



**INCLUDES** COST OF TOPSIDES

**CRI** COST **BASED** ON 0 **KM** HAUL DISTANCE

**CRI** - Caisson **Retained** island
CPS - Conical Production Structure

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Figure 2.0-3. Production platform capital cost versus water-depth.

# 3.0 ENVIRONMENTAL AND RESOURCE EVALUATION BASIS

## 3.1 ENVIRONMENTAL DESIGN CRITERIA

The Beaufort Sea environment, especially in water depths beyond the landfast ice zone, is extremely severe in comparison to other areas of the world where offshore petroleum development is taking place. The capital and operating costs required for the exploration, production and transportation of petroleum reserves from the study area are directly related to the environmental constraints placed upon these systems. Exploration and production platforms must be designed for the predominate ice, wave, current, water depth and geotechnical conditions. Pipeline costs will vary with the water depth, soil and surface ice conditions. The cost of crude oil transportation by tanker is highly dependent on ice coverage and thickness. Supply operations will also depend on ice coverage and thickness. Hence, every aspect of petroleum development is affected by the design, construction and operation limitations imposed by environmental factors.

The following paragraphs discuss the general methodologies and assumptions used for the determination of the following environmental parameters:

- ice conditions
- waves
- water depth
- winds
- currents
- tides/storm surge
- geotechnical conditions
- geology and geologic hazards
- meteorological conditions
- daylight duration

Specific design values for the above list of environmental parameters are given for exploration, production and transportation activities in the study area.

The specific environmental design criteria values presented below have a deterministic basis, primarily aimed at identifying maximums. This approach is acceptable for purposes of this report but is not sufficient for site-specific assessments. It is important that the risks and uncertainties associated with the use of design criteria be estimated and accounted for. The environmental loading and structural resistance uncertainties in the Arctic are greater than those in less hostile environments and are particularly difficult to come to terms with. However, every attempt should be made to deal with these uncertainties from a reliability-based approach to design.

### 3.1.1 Ice Conditions

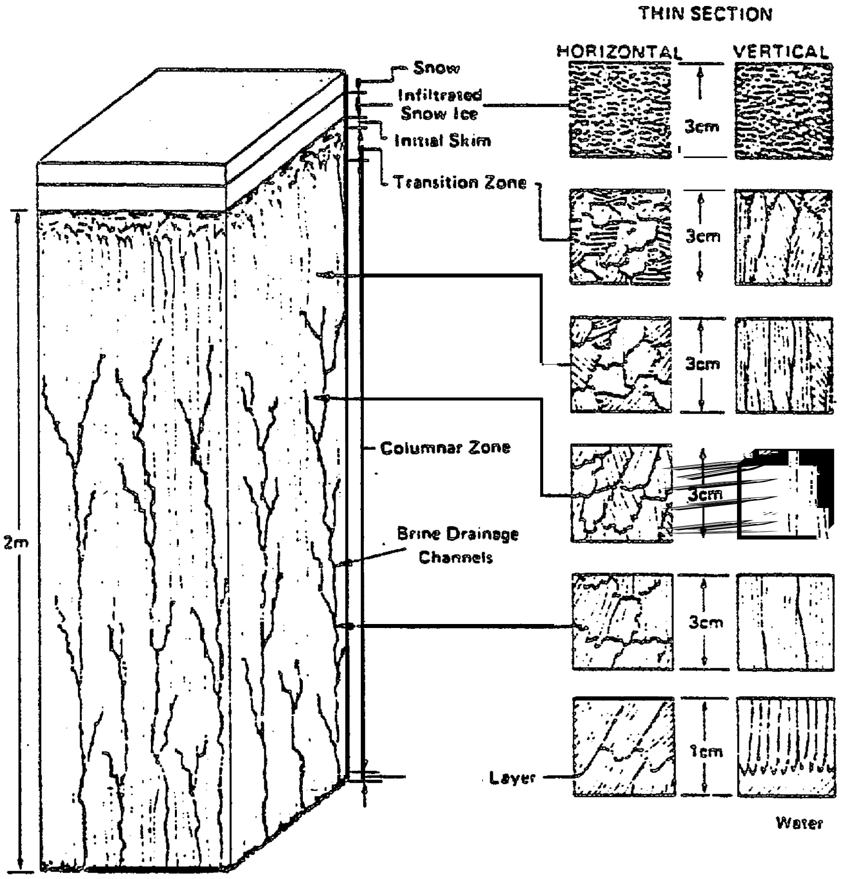
The major environmental hazard in the Alaskan Beaufort Sea is moving ice, which may be classified into three broad categories: annual ice, multi-year ice, and ice islands. As will be evident later in this section, however, there is a continuum of ice features, ranging in severity from annual ice to ice islands, and the separation is not clear-cut. For purposes of offshore exploration and production structure preliminary designs and icebreaking vessel trafficability, the ice conditions discussed herein are a current appraisal of the present state of knowledge as available in the open literature. Several areas are identified where research is in progress or is needed.

The discussion of ice conditions is presented in the following sequence:

a) ice strength
b) ice modulus of elasticity
c) level ice characteristics
d) ice ridge characteristics
e) ice islands
f) ice coverage and concentration
g) ice drift velocity
h) ice coefficient of friction
i) superstructure icing rate

### a) Ice Strength

The compressive strength of annual sea ice has been investigated by many researchers, and is a function of salinity, temperature, crystalline structure, and strain rate. First year sea ice has a crystal structure variation with thickness as illustrated in Figure 3.1-1 (Schwarz and Weeks, 1977). Granular ice is found near the top, with unoriented columnar crystals below, and oriented columnar crystals near the bottom of the ice sheet. These three representative types of annual sea ice result in a salinity profile as shown typically in Figure 3.1-2 (Weeks and Assur, 1967). Compressive strengths at -10°C have been published (Wang, 1979) for these three types of ice as a function of strain rate. Values range from 1.25 mPa (180 psi) at $10^{-6}sec^{-1}$ strain rate to 10 mPa (1500 psi) at $10^{-3}sec^{-1}$ strain rate, for the granular sea ice, which is strongest. The effect of sample orientation on compressive strength is plotted specifically in Figure 3.1-3 for a strain rate of $10^{-3}$ see-l. The columnar ice is weakest for an angle of 45° between the applied load and the c-axis, which is horizontal below the 20 cm depth, corresponding to a vertical orientation of ice platelets and brine inclusions. The brine inclusions undergo a transition in their size and their contribution to overall ice strength at a temperature of -8.7°C, where the solid hydrate $Na_2SO_4 \cdot 10\ H_2O$ is formed, and at -22.7°C, where the hydrate crystal $NaCl \cdot 2\ H_2O$ is formed. Thus the strengths are a function of temperature. Data presented on compressive strength of Baltic Sea ice (Schwarz and Weeks, 1977) in Figure 3.1-4 suggests that a strength reduction of a factor of about 2.0 to 2.5 takes place as sea ice is warmed from -10”C to O“C, but this depends upon orientation and strain rate. A linear variation of temperature is commonly measured as a function of depth in annual sea



Source: and Weeks, 1977

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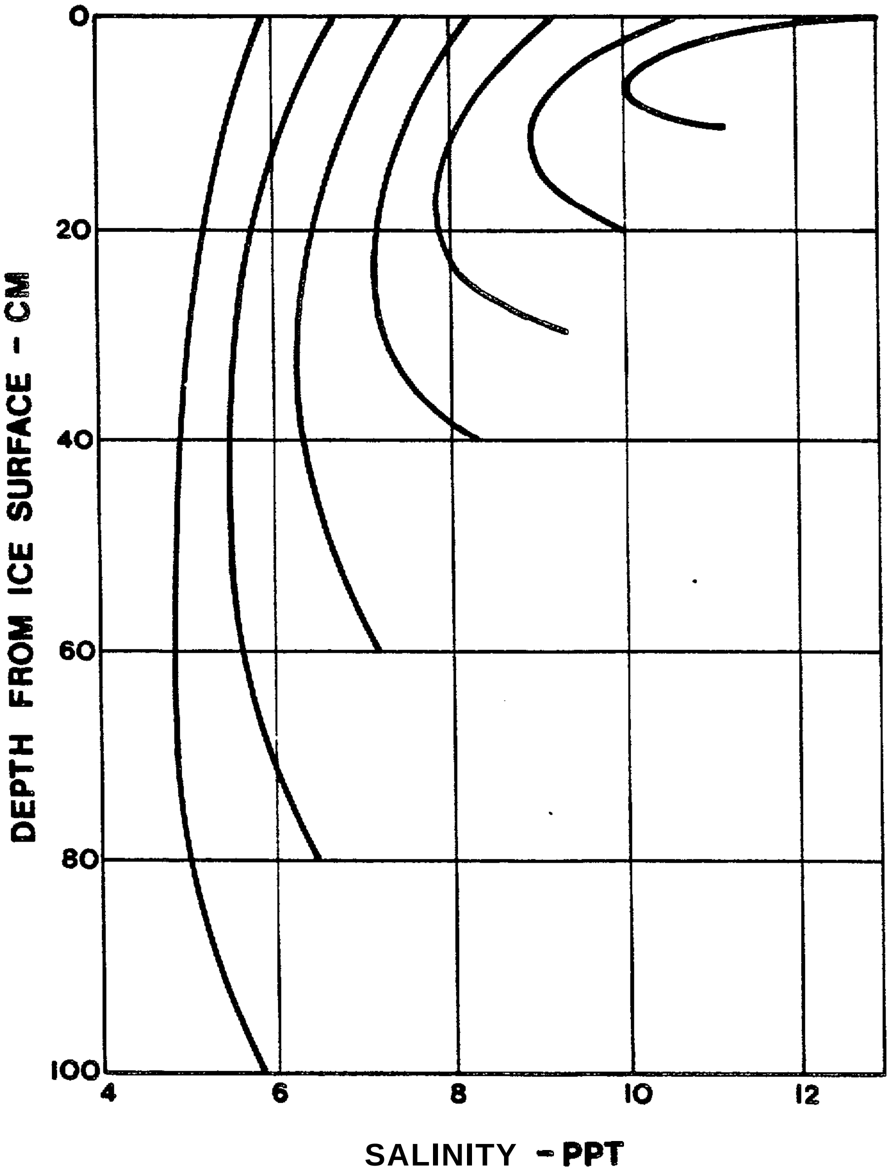
Figure 3.1-1. Schematic drawing showing several aspects of the structure of annual sea ice.



Adapted from: Weeks and Assur, 1967

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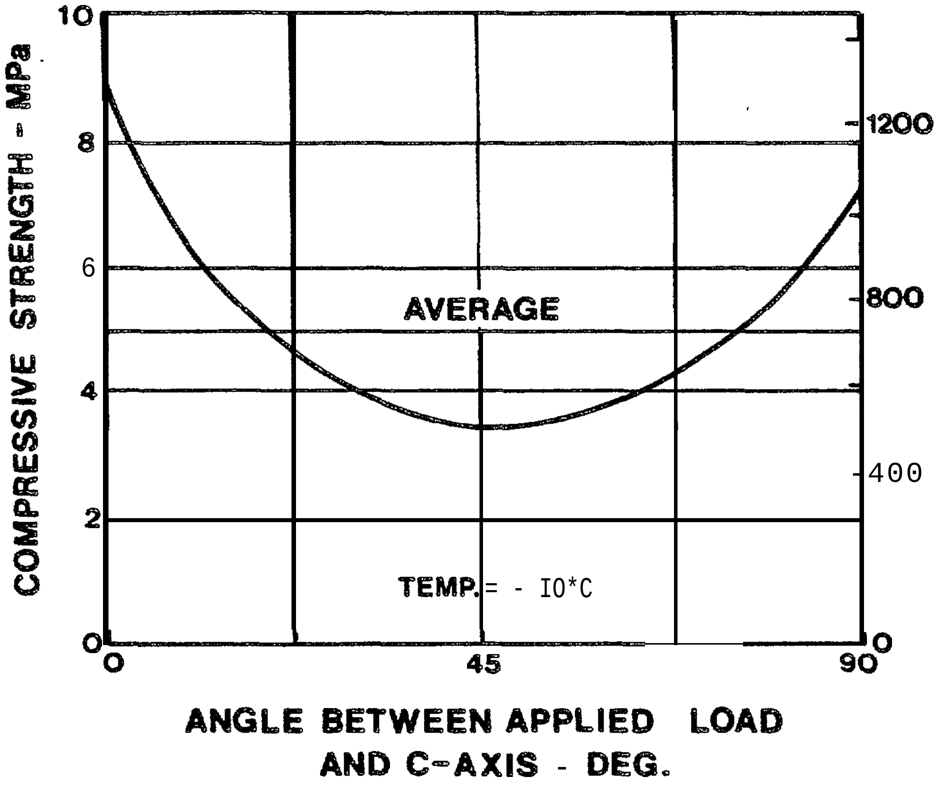
Figure 3.1-2. Schematic salinity profiles for annual sea ice of various thicknesses.



Adapted from: Wang, 1979

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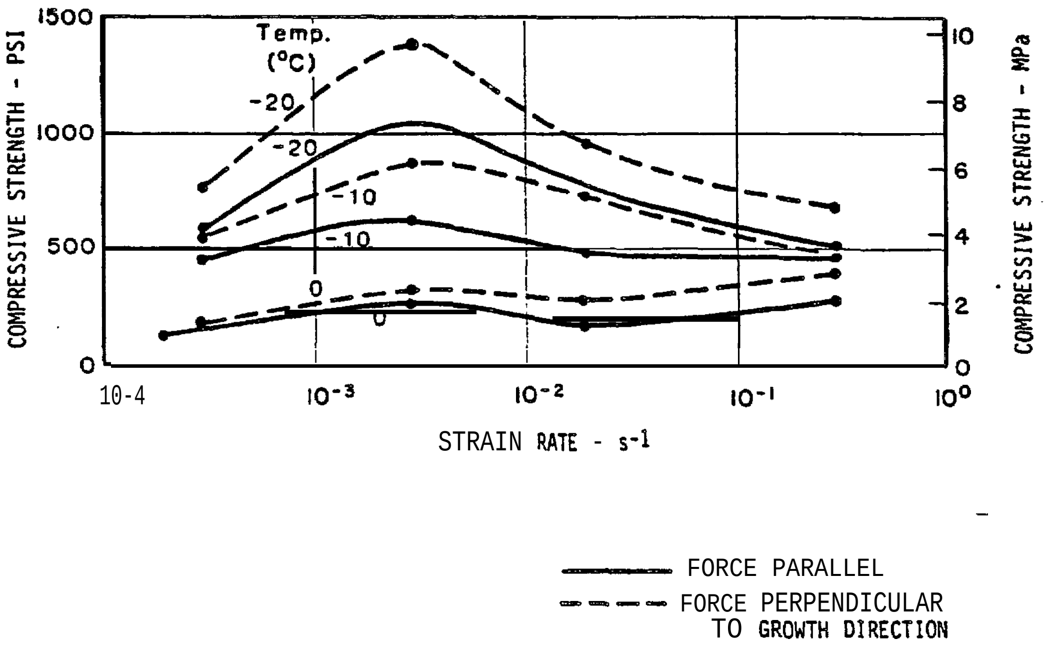
**Figure** 3.1-3. Maximum compressive strength of oriented columnar annual sea ice as a function of sample orientation.



Adapted from: Schwarz and Weeks, 1977

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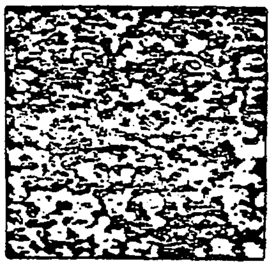
Figure 3.1-4. Compressive strength of Baltic Sea ice as a function of strain rate, temperature, and orientation of the force.

ice, and with a water temperature of -1.8°C, it is obvious that the lower portion of the annual ice sheet is quite weak.

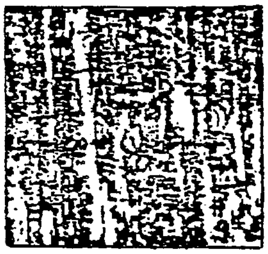
The compressive strength of multi-year sea ice has been investigated by the oil industry in numerous proprietary studies over the past ten years but only recently has the results of a comprehensive program been reported by Cox et al. (1984). Their data show that compressive strength is a function of temperature arid strain rate. However, from data included in their paper, compressive strength was also shown to be a function of porosity. Since multi-year ice is composed of mechanically deformed and fractured annual ice, which has been subjected to several melting-refreezing episodes, it is a more complicated structure and has been classified by Richter and Cox (1984) into eight sub-types as shown in Figure 3.1-5. This structural variability gives rise to a large variation in compressive strengths. Considering the wide variation in the available data, a statistical analysis by Weeks (1984) was undertaken to examine strength as a function of depth. No significant variation in strength was evident from his analysis. His explanation is that the low porosity in the ridge keels and high porosity in the ridge sails is partially offset by the slightly higher salinity of the ridge keels (about 0.8 ppt greater than the sails), but that the random statistical variations in internal structure obscure this. When using this data, the failure of multi-year ridges against structures is likely to take place at regions with weak structural strength within the ridge, below the mean strength va"lues reported by Weeks

## STRUCTURAL CLASSIFICATION SCHEME
## FOR MULTI-YEAR PRESSURE RIDGE ICE SAMPLES

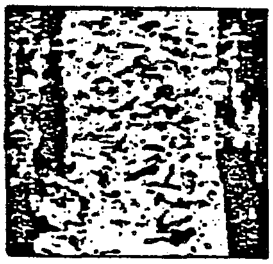
| Ice Type | Code | Structural Characteristics |
|---|---|---|
| Granular | I | Isotropic, equiaxed crystals |
| Columnar | II | Elongated, columnar grains |
| | IIA | Columnar sea ice with c-axes normal to growth direction; axes may or may not be aligned in this plane |
| | IIB | Columnar sea ice having random c-axis orientation (transition ice) |
| | IIC | Columnar freshwater ice; may be either anisotropic or isotropic |
| Mixed | III | Combination of Types I and II |
| | 111A | Largely Type II with granular veins |
| | IIIB | Largely Type I with inclusions of Type I or II ice (brecciated ice) |



**Granular Ice (Type I)**



**Columnar Ice (Type II)**



Heeled **Fracture (Type IIIA)**

**Brecciated (Type IIIB)**

**cm**

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Source: Richter and Cox, 1984

Figure 3.1-5. Structural characteristics of multi-year sea ice types.

(1984). Data thus presented by Weeks (1984) are from cores in the top 6 m (20 ft) at several locations in multi-year ridges, but whether this can be extrapolated to deeper multi-year ridges or to all types of multi-year ridges is not yet established.

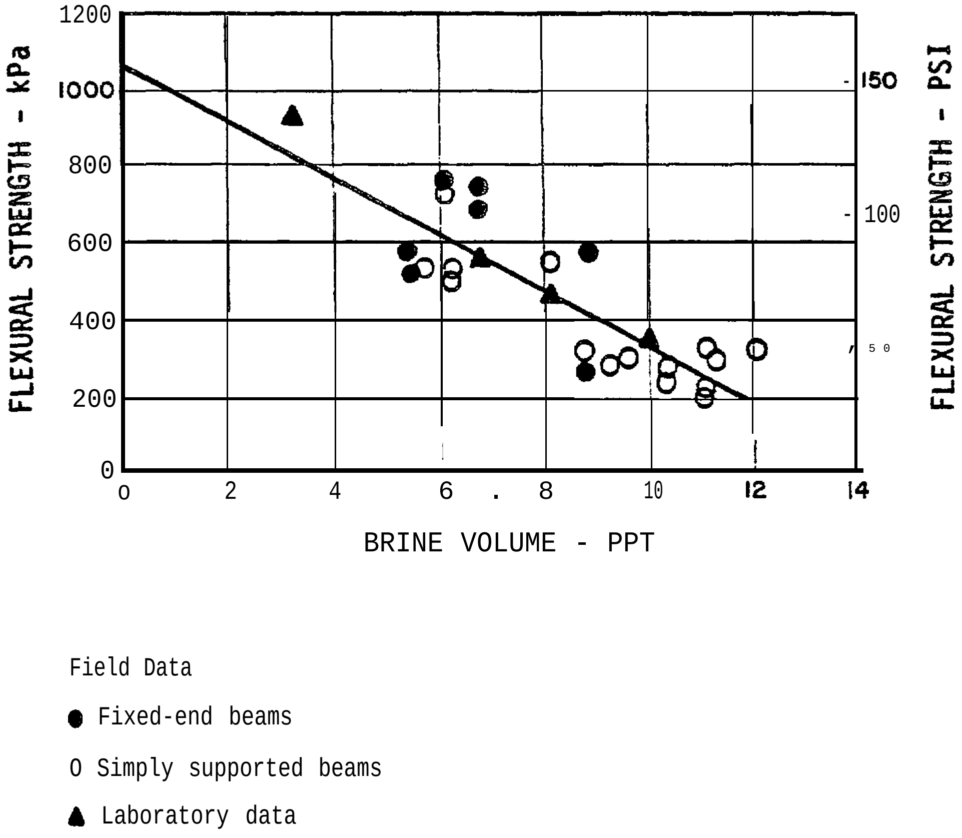
Flexural strength of annual sea ice as a function of brine volume is presented in Figure 3.1-6 (Dykins, 1971), and in Figure 3.1-7 the variation of flexural strength as a function of temperature is given (Katona and Vaudrey, 1973). The relationship between brine volume, salinity, and temperature has been given by Frankenstein and Garner (1967) as:

$$b_v = S(0.532 - \frac{49.185}{t})$$

where S is salinity in parts per thousand (ppt), $b_v$ is brine, volume in ppt, and t is the ice temperature in degrees centigrade. A more recent paper (Vaudrey, 1977) suggests a slightly revised relationship for flexural strength:

$$s_f = 960[1.0 - 0.063 (b_v)^{0.5}]$$

where $s_f$ is flexural strength (kPa) and $b_v$ is brine volume in ppt. No results of flexural strength of multi-year ice are available, but a calculation by Karp (1980) has assumed values based on average multi-year ice salinity and temperature profiles with depth. In view of the more recently developed information about the variations in internal structure of multi-year ice as essentially a composite material , discussed briefly above, it would be presumptions to take this approach. The internal flaws in multi-year sea ice obviously



Adapted from: **Dykins,** 1971

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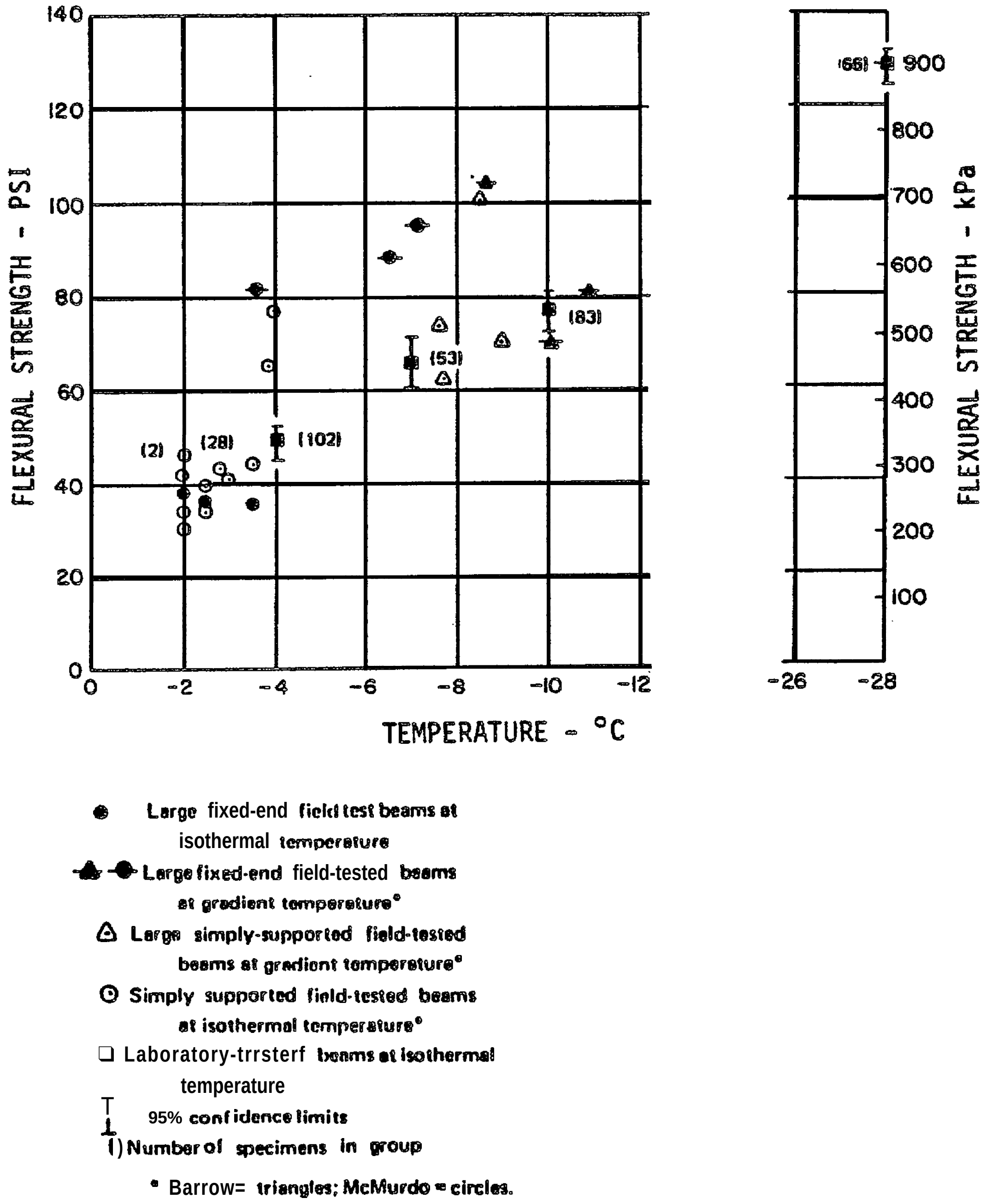
Figure 3.1-6. **Flexural** strength of annual sea ice versus brine volume.



Adapted f rem: Katona and Vaudrey, 1973

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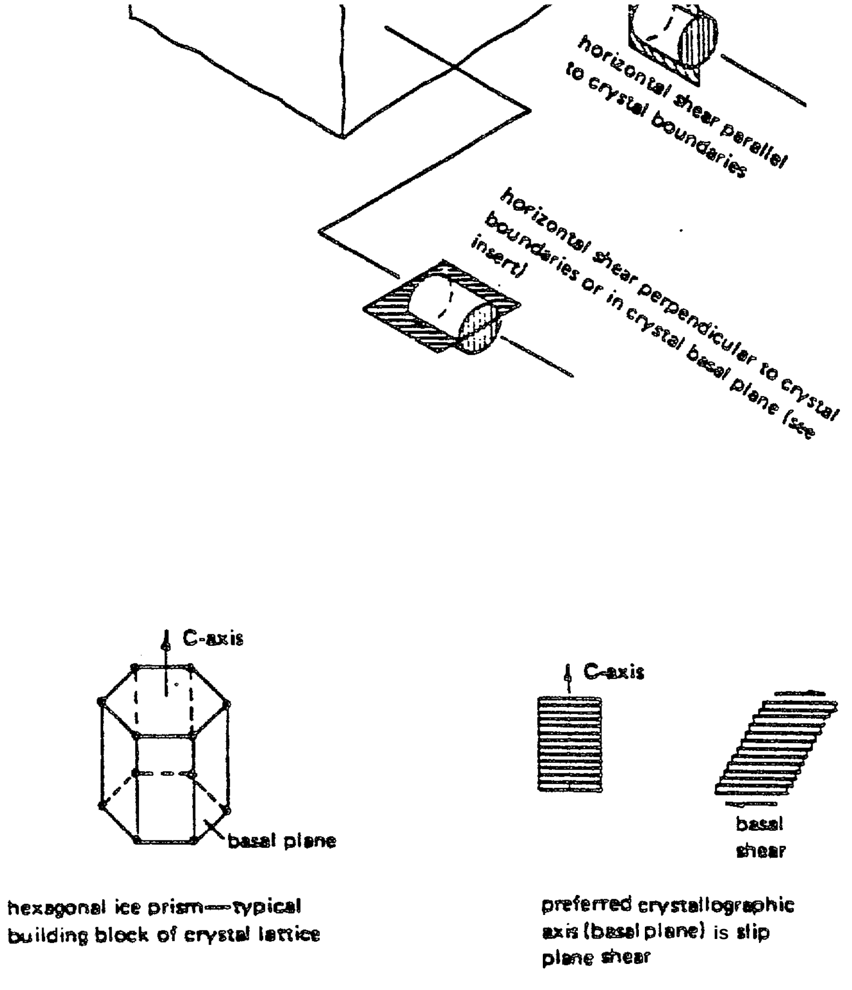
Figure 3.1-7. Flexural strength of annual sea ice versus temperature.

dominate the strength of large multi-year floes and ridges, whether compressive or flexural failures are involved. Further research is needed in this area.

Shear strength of annual sea ice has been presented as a function of brine volume by Paige and Lee (1967). A dependence of these results upon loading rate has been suggested by Katona and Vaudrey (1973), but the actual loading rate used in the field tests of Paige and Lee (1967) is not known. They represent conservative values, however, and can be used in the absence of more detailed results. The values obtained by Katona and Vaudrey (1973), as shown in Figures 3.1-8 through 3.1-11, illustrate temperature and crystallographic dependence of shear strength, as well as salinity dependence. No data are available for multi-year ice, but the low-salinity data from Katona and Vaudrey may apply to -level multi-year ice (not to ridges).

A discussion of ice strengths appropriate to ice islands is deferred to a-later section of this report, after ice islands have been described in more detail. No direct measurements are available for the strength of the ice from ice islands.

For preliminary design purposes, the following ice strengths have been used:



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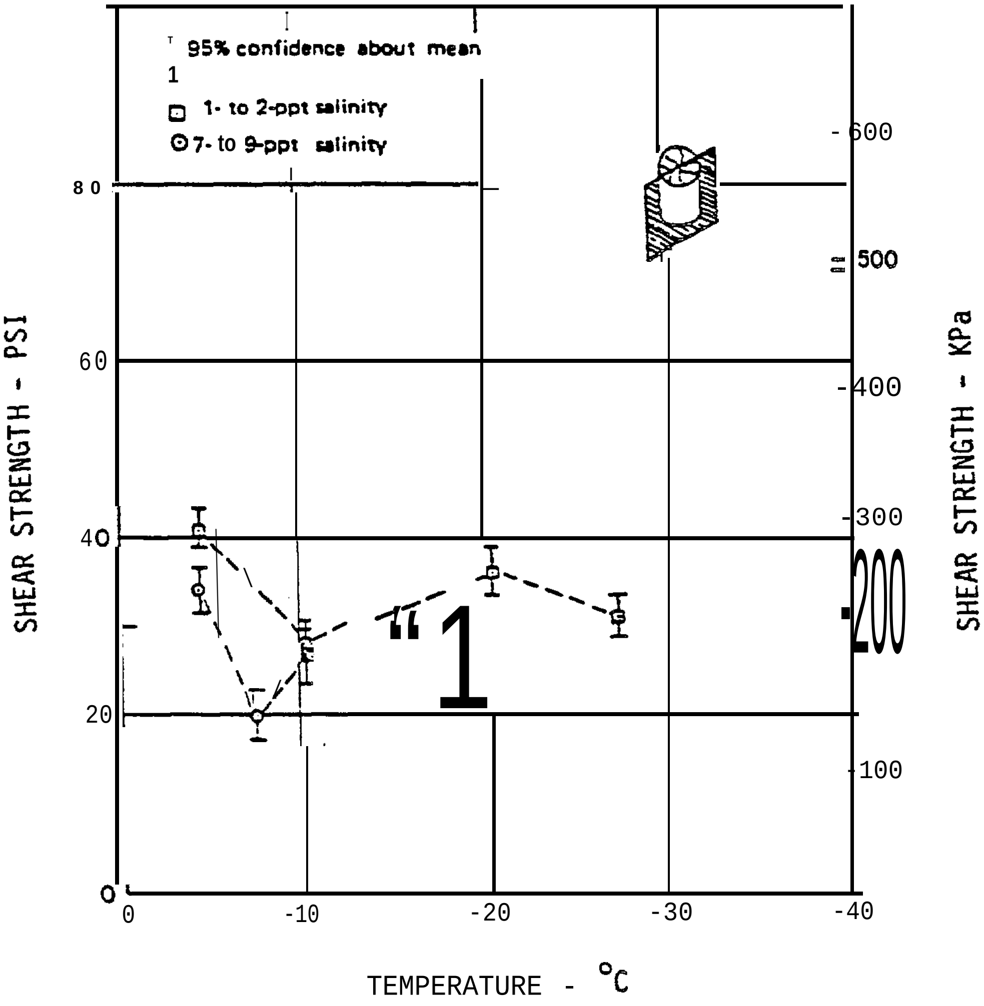
Source: Katona and Vaudrey, 1973

Figure 3.1-8. Orientation of shear planes in the experimental Investigations of annual sea ice shear strength.



Adapted from: Katona and Vaudrey, 1973

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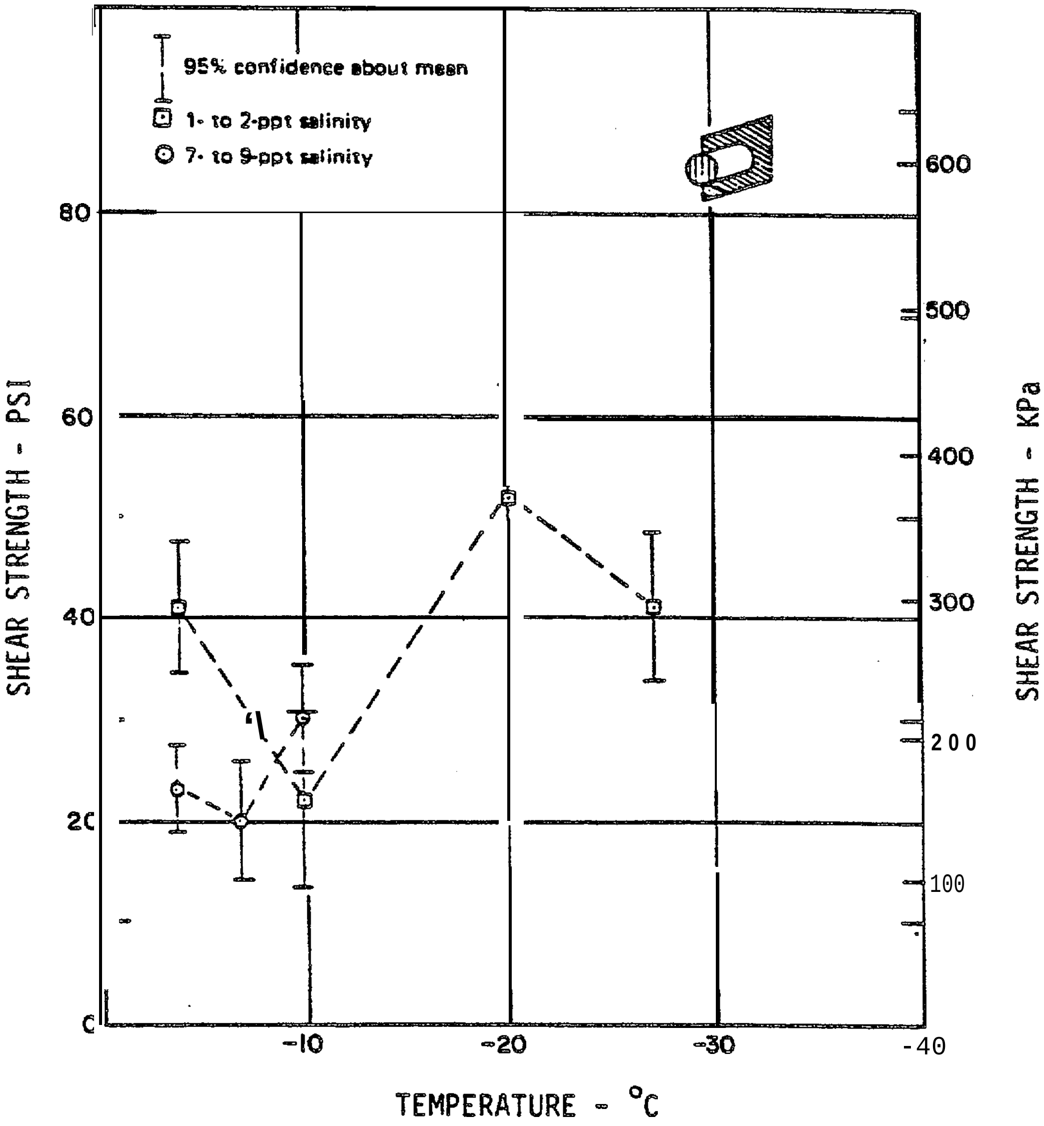
Figure 3.1-9. Confined shear strength (vertical) versus temperature.



Adapted from: **Katona and Vaudrey, 1973**

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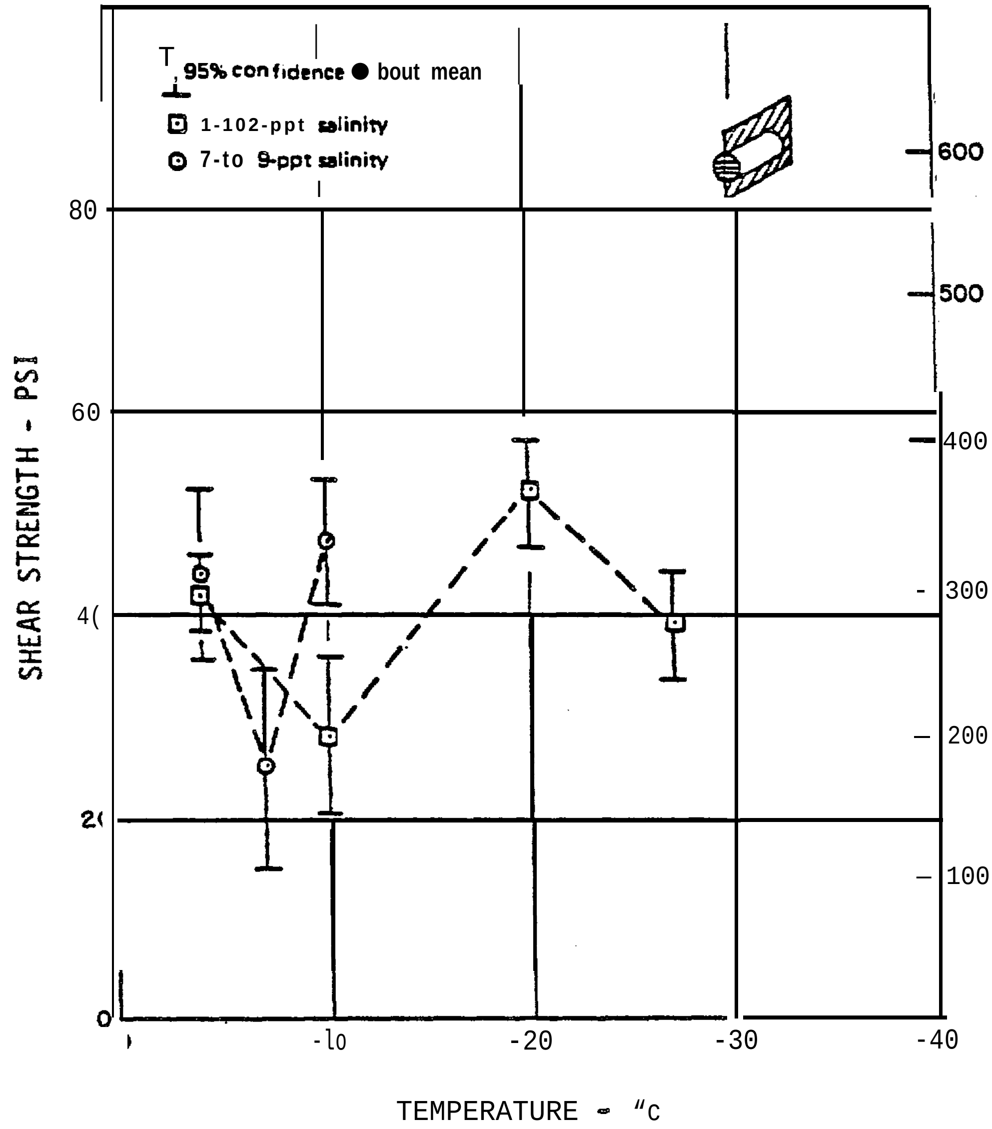
Figure 3.1-10. Confined shear strength (horizontal and parellel to crystal boundary) versus temperature.



Adapted from: **Katona** and **Vaudrey,** 1973

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Figure 3.1-11. Confined shear strength (horizontal and perpendicular to the crystal boundary) versus temperature.

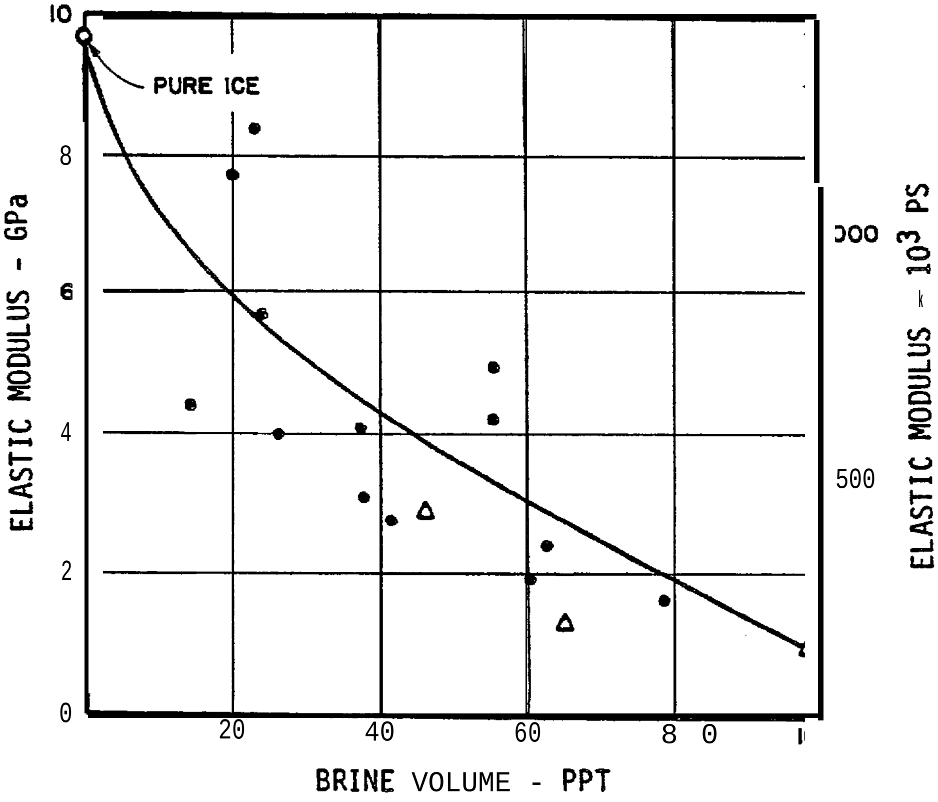
| Annual Ice | |
|---|---|
| Compressive | 5,900 kPa (850 psi) |
| Flexural | 620 kPa ( 90 psi) |
| Shear | 1,000 kPa (150 psi) |

| Multi-year Ice | |
|---|---|
| Compressive | 8,300 kPa (1,200 psi) |
| Flexural | 760 kPa ( 110 psi) |
| Shear | 1,400 kPa ( 200 psi) |

### b) Ice Modulus of Elasticity

" The modulus of elasticity of annual sea ice has been measured by seismic means (Anderson, 1958) and by static measurements (Dykins, 1971), as shown in Figure 3.1-12 as a function of brine volume. Small-sample acoustic measurement results from Langleben and Pounder (1963) are shown in Figure 3.1-13. Because of the creep of annual sea ice at high temperatures, elastic-modulus values obtained by large-scale beam tests differ from data obtained by acoustic methods, as shown by Katona and Vaudrey (1973). The most recent compilation of beam test data by Vaudrey (1977) is shown in Figure 3.1-14 and is probably most useful in calculations of flexural failure of ice sheets against sloping structure faces.

The initial tangent modulus of multi-year ice was obtained by Cox et al. (1984). These values are not strongly dependent upon



Elastic modulus of sea ice as determined by seismic measurements vs. brine volume (Anderson, 1958). The three triangular points are from static tests performed by Dykins (1971).

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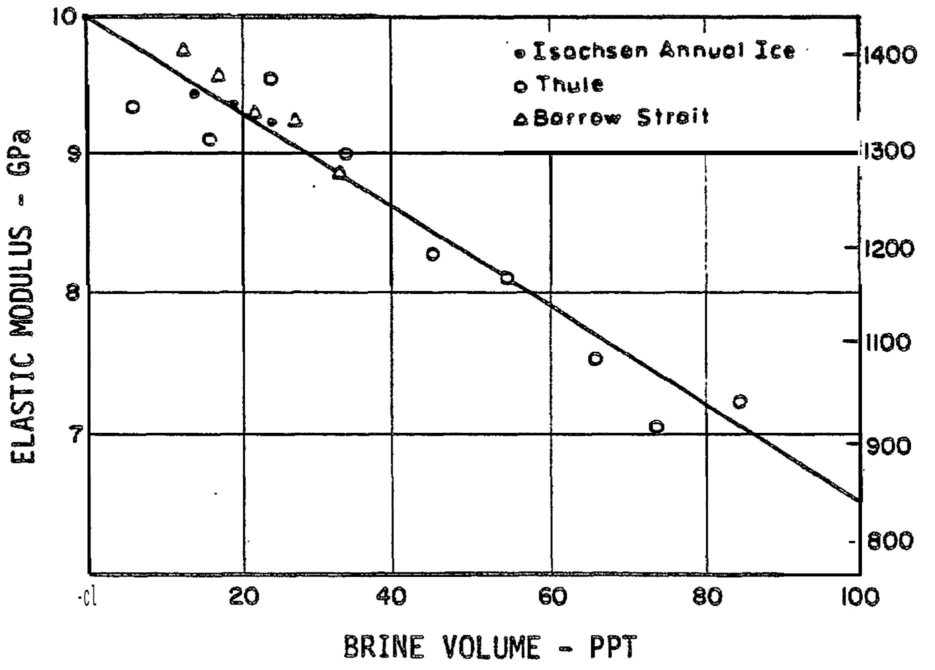
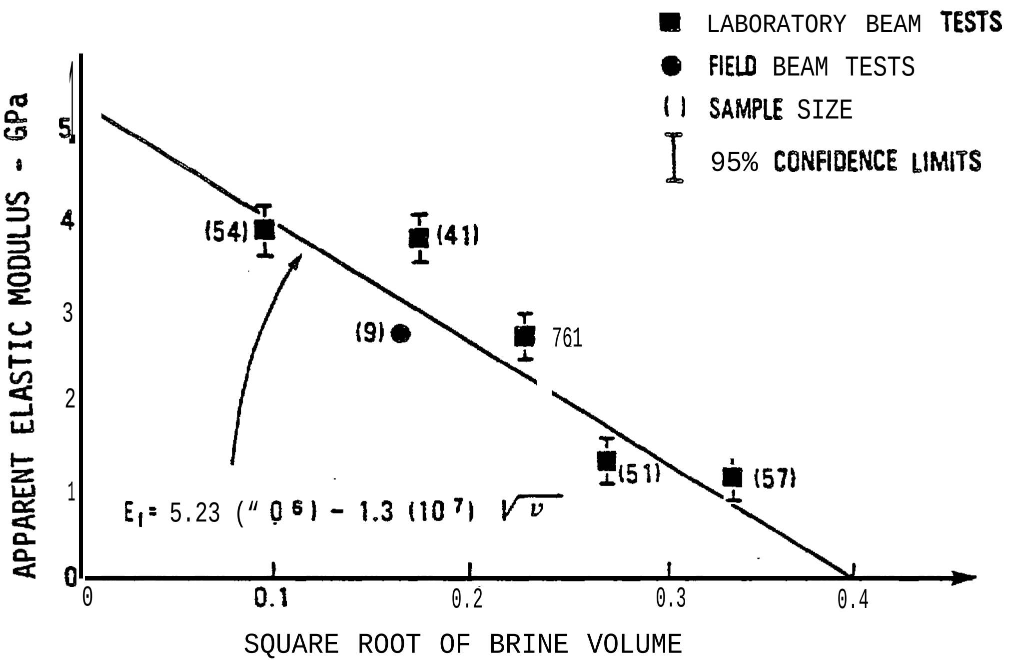
Figure 3.1-12. Seismic measurements of elastic modulus of annual sea ice versus brine volume.



Adapted from: Langleben and Pounder, 1963

**Figure 3.1-13.** Acoustic measurements of elastic modulus of annual sea ice versus brine volume.



Adapted from: Vaudrey, 1977

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Figure 3.1-14. Apparent modulus of elasticity of annual sea ice versus the square root of brine volume.

porosity or upon temperature, but there is an obvious difference between values taken at two different strain rates, $10^{-3}$ and $10^{-5}$ $sec^{-1}$. A summary of this data is given in Figure 3.1-15 (after Cox et al., 1984). This set of results is similar to those of Traetteberg et al. (1975) who studied naturally-formed granular freshwater ice and laboratory-grown columnar-grained ice. Traetteberg et al. ( 1975) presented the dependence of Young's modulus upon strain rate, temperature, and time. These values can be compared with that obtained from the formula derived by Vaudrey (1977 ) from beam test results: $E(psi) = 10^3[771 - 63.2(b_v)^{0.5}]$, where $b_v$ is brine volume in ppt. The results are comparable.

The elastic modulus of ice island ice is quite probably in the same range, and the same formula will be used as a first approximation until actual data are obtained.

For preliminary design purposes, the following modulus of elasticity has been used:

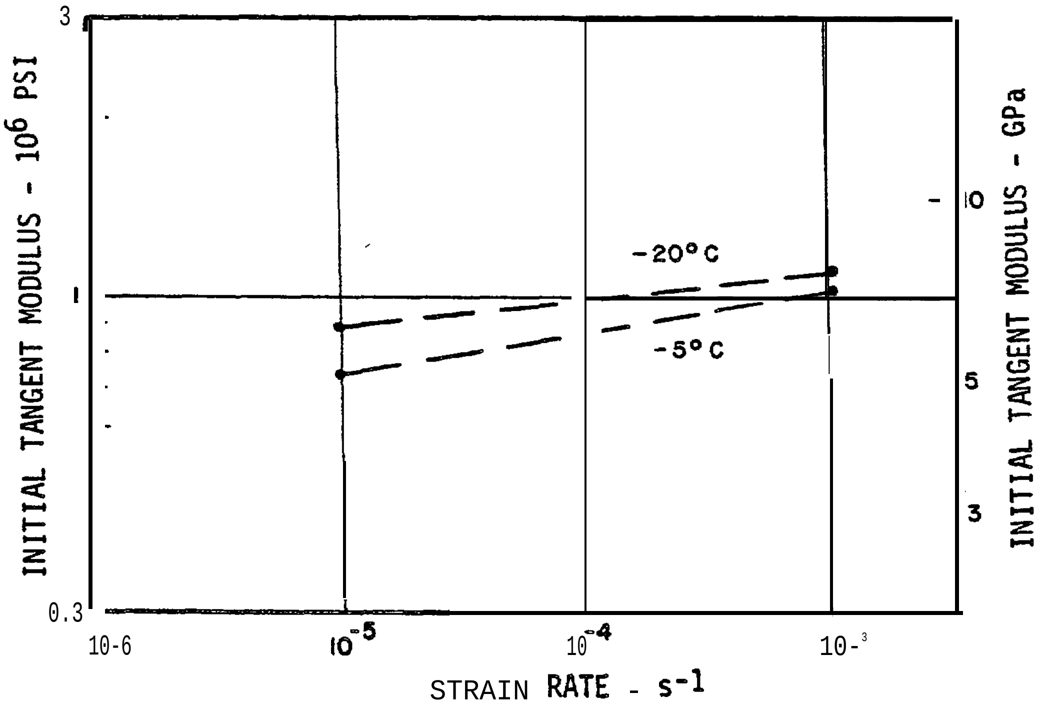
Annual Ice

Modulus of Elasticity = 3,000 mPa (435,000 psi)

Multi-year Ice

Modulus of Elasticity = 3,800 mPa (550,000 psi )

| | INITIAL TANGENT MODULUS | | | | | | |
|---|---|---|---|---|---|---|---|
| | Maximum | | Minimum | | Mean | | |
| | (GPa) | (lbf/in.$^2$x$10^6$) | (GPa) | (lbf/in.$^2$x$10^6$) | (GPa) | (lbf/in.$^2$x$10^6$) | Number of samples |
| °C (23°F) | | | | | | | |
| $10^{-5}$ $s^{-1}$ | 10.34 | 1.500 | 2.41 | 0.350 | 5.02±1.57 | 0.728±0.228 | 70 |
| $10^{-3}$ $s^{-1}$ | 9.86 | 1.430 | 4.95 | 0.718 | 6.99±1.12 | 1.014±0.162 | 70 |
| 0°C (-4°F) | | | | | | | |
| $10^{-5}$ $s^{-1}$ | 10.48 | 1.520 | 3.45 | 0.500 | 5.95±1.19 | 0.863±0.172 | 40 |
| $10^{-3}$ $s^{-1}$ | 10.38 | 1.570 | 4.89 | 0.709 | 7.62±1.19 | 1.105±0.173 | 40 |



AVERAGE INITIAL TANGENT MODULUS OF RIDGE ICE SAMPLES VS. STRAIN RATE FOR TESTS AT -5°C (23°F) AND -20°C (-4°F).

Adapted from: Cox, Richter, Weeks and Mellor, 1984

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Figure 3.1-15. Summary of initial tangent modulus data for multi-year ridge ice.

## c) Level Ice Characteristics

Annual sea ice in the Alaskan Beaufort Sea originates at a wide variety of locations within the entire Beaufort Gyre, which are subject to a variety of cumulative degree-days of freezing during the winter season. It is therefore impractical to simply calculate the expected thickness of annual ice in the moving Gyre from standard formulae such as that given by Zubov (1945). The annual ice will be present in varying thicknesses and floe sizes in the shear zone, which is within the region of 20 to 90 m (65 to 300 ft) water depth, because of the virtually continual movement of the Gyre with respect to the landfast ice. The large amount of open water thus created refreezes rapidly at first, then more slowly, and the shear zone annual ice which moves and fractures against an offshore structure varies in thickness from 10 cm to 1 m (4 in. to 3 ft), based upon qualitative observations at the Dome Petroleum Single Steel Drilling Caisson (SSDC) in the Canadian Beaufort Sea (M. Metge, personal communication with W. Sackinger). In the shear zone, then, annual ice is actually thinner than in the landfast zone, and is often cracked and broken, as it is the weakest category of ice in that region. The question of floe size thus is of no importance, and the forces involved during the fracture of annual ice in the shear zone are relatively low. In most cases, the annual ice serves as a very fragile buffer material between a structure and the strong multi-year ice inclusions and ice island inclusions within the composite ice pack in the shear zone.

The most serious problem in terms of forces arises when the annual ice is almost entirely absent, or has been converted into annual ice ridges, and a significant amount of multi-year ice is available over a large region to apply forces upon a structure. Weather conditions which could produce this are those which drive the pack ice directly towards the shoreline in compression for several days continuously; this occurs infrequently, and a detailed statistical estimate of the probability of such weather conditions is not yet available. Under normal weather conditions, however, the shear zone is a region where ample annual ice of thickness less than 2 m (6.5 ft) is available to fracture and absorb energy of the moving pack, either building rubble in front of a wide structure or passing rubble around a narrow structure.

The thickness of level multi-year Ice should be considered as a variable depending upon its region of origin. In the southern Beaufort Gyre, calculations of an equilibrium thickness of 3 to 5 m (10 to 16 ft) have been made for multi-year ice. The balance between freezing and summer ablation varies, however, and in the most severe region of multi-year ice formation, considered by the study team to be along the northern coast of Ellesmere Island, the multi-year ice can be lodged in bays and inlets, where it is growing in thickness for many years. In 1980, for example, Serson measured multi-year ice thickness of 7 m (23 ft) in the ice plug in Nansen Sound, between Ellesmere and Axel Heiberg Islands (Sackinger et al., 1984). In April 1980, Serson also observed a large piece of multi-year ice which had a thickness of 10 m (33 ft) (Sackinger et al., 1984), breaking away from the shoreline at Cape Fanshawe-Martin. The multi-year ice which has been in place in Yelverton Bay for at least two decades is presently 9 m (30 ft) thick (M. Jeffries, personal communication with W. Sackinger). It seems reasonable to assume that the level multi-year ice drifting in the Beaufort Gyre, which obviously contains ice from these regions, will have a distribution of ice thicknesses up to the 10 m (33 ft) value. Airborne laser profilometer flights have usually been oriented towards the question of ridge height distributions, particularly in the shear zone, and thus have not been analyzed for this type of data.

The ice islands could be considered as level ice, but will instead be discussed separately.

For preliminary design purposes, the following level ice characteristics have been used:

| Annual Ice | EXPLORATION | PRODUCTION |
|---|---|---|
| Average salinity | 6 ppt | 6 ppt |
| Average temperature | -10°C | -10°C |
| Maximum thickness | 2 m (6*5 ft) | 2 m (6.5 ft) |

| Multi-year Ice | | |
|---|---|---|
| Average salinity | 3 ppt | 3 ppt |
| Average temperature | -15°C | -15°C |
| Maximum thickness | 6 m (20 ft) | 10 m (33 ft) |

### d) Ice Ridge Characteristics

The ridges in the Alaskan Beaufort Sea can be categorized according to their age (annual ridges which have formed within the present winter and multi-year ridges which have survived one or more summer melt seasons). An additional basis of classification is whether the ridge was formed by a shearing movement between two ice floes, or by a compressive movement between the floes. Another basis of classification which could be used is whether the ridges formed closely enough to the shoreline to become grounded during the formation process, or whether they formed in deeper waters of the Beaufort Sea and did not become grounded during formation. Ridges of all of these types have been observed visually and have been photographed, but many of the instruments used to collect ridge data are not capable of providing the discrimination among the ridge types described above. Several generalizations can be made, however. First, the interaction of the pack ice in the shear zone is most frequently shearing motion, leading to the formation of shear ridges, which are composed of rather small blocks and fragments of ice, and which result in very large piles of ice at points of concentration of this ice debris along a small corner along the extended line of shear motion. When this takes place in water depths of less than about 25 m (82 ft), such piles of ice often become grounded and the ratio of keel depth to sail height is affected thereafter during the ridge forming process, leading to more ice above the waterline than would be expected based upon considerations of isostatic equilibrium. It should also be noted that compressive motions can often take place along a shoreline, building large compressive ridges with block sizes a few times their thickness, and again grounding in water depths of less than 25 m (82 ft), building to a greater height than would be expected from isostatic equilibrium. Compressive motions are less common along the Alaskan coast, but are quite common along the Canadian coast of Banks and Prince Patrick Islands. The ridges formed there eventually make their way to the Alaskan Beaufort Sea, and deserve most serious consideration.

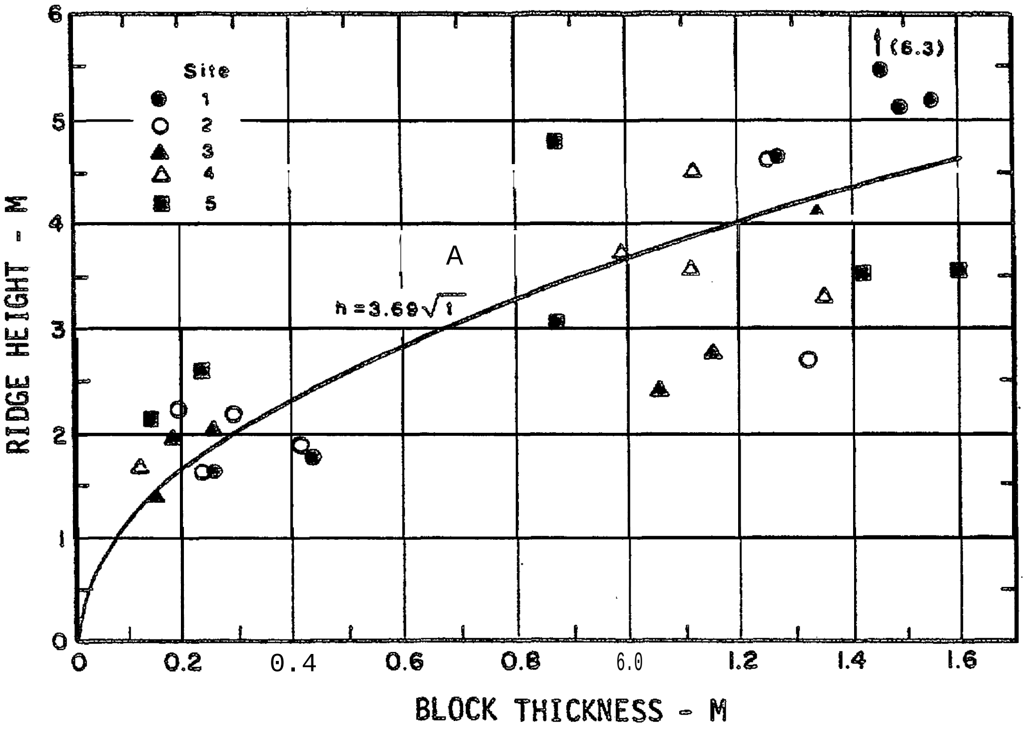
B

First year ridges, or annual ice ridges, are generally composed of random-oriented blocks with many voids, and are held together by the freezing of the points and lines of contact between blocks which takes place shortly after the blocks are broken and piled. Above the waterline, this bonding is not great, and the voids between the blocks are gradually filled with drifting snow. Below the waterline, there is a cold reserve in the newly-piled blocks which may freeze 20 to 40 percent of the void volume, depending upon the season of formation. New ice then forms gradually within the ridge core, but more slowly than in a level ice situation because of the greater impediment to heat flow provided by the snow-filled ridge of ice above. Ridge sectioning has been done on a few occasions in the Beaufort Sea (Vaudrey, 1979; Ralston, 1979; Gladwell, 1976; Sisodiya and Vaudrey, 1981). A consideration of this data by Ralston (1979) led to the recommendation that a maximum total thickness of 3 m (10 ft) for such refrozen rubble was realistic. In many cases, the refrozen layer will be less than this value, but in at least one instance (Sisodiya and Vaudrey, 1981) multiple-rafting produced values greater than 6.7 m (22 ft). The sail of newly-formed ridges can be as high as 22 m (72 ft) above sea level, grounded in 18 m (59 ft) water depth, and with areal dimensions 107 m by 335 m (350 ft by 1100 ft.) (Sisodiya and Vaudrey, 1981). A specific study of the relationship of block thickness to ridge height for first-year pressure ridges in the coastal region north of Prudhoe Bay has been made by Tucker and Govoni (1981) and their result is shown in Figure 3.1-16. The higher ridges were composed of thicker ice, which is not surprising if compressive movements are involved, as thicker ice can support greater pack ice stress and transmit greater forces to the base of the ridge during the ridgebuilding event. According to reports from ships operating in ice, however, first-year ridges do not offer significant resistance above that required to push the large volumes of ice in the ridges out of the way.

If a ridge is in isostatic equilibrium, the ratio of the freeboard, f, to the draft, z, can be calculated at any point by using the equation:

$$f/z = k_f(p_w - p_i) / k_d p_i$$

where $k_f$ and $k_d$ are the solidifies of the above- and below-water portions of the ridge and pi and $p_w$ are the densities of sea ice and



Source: Tucker and Govoni, 1981

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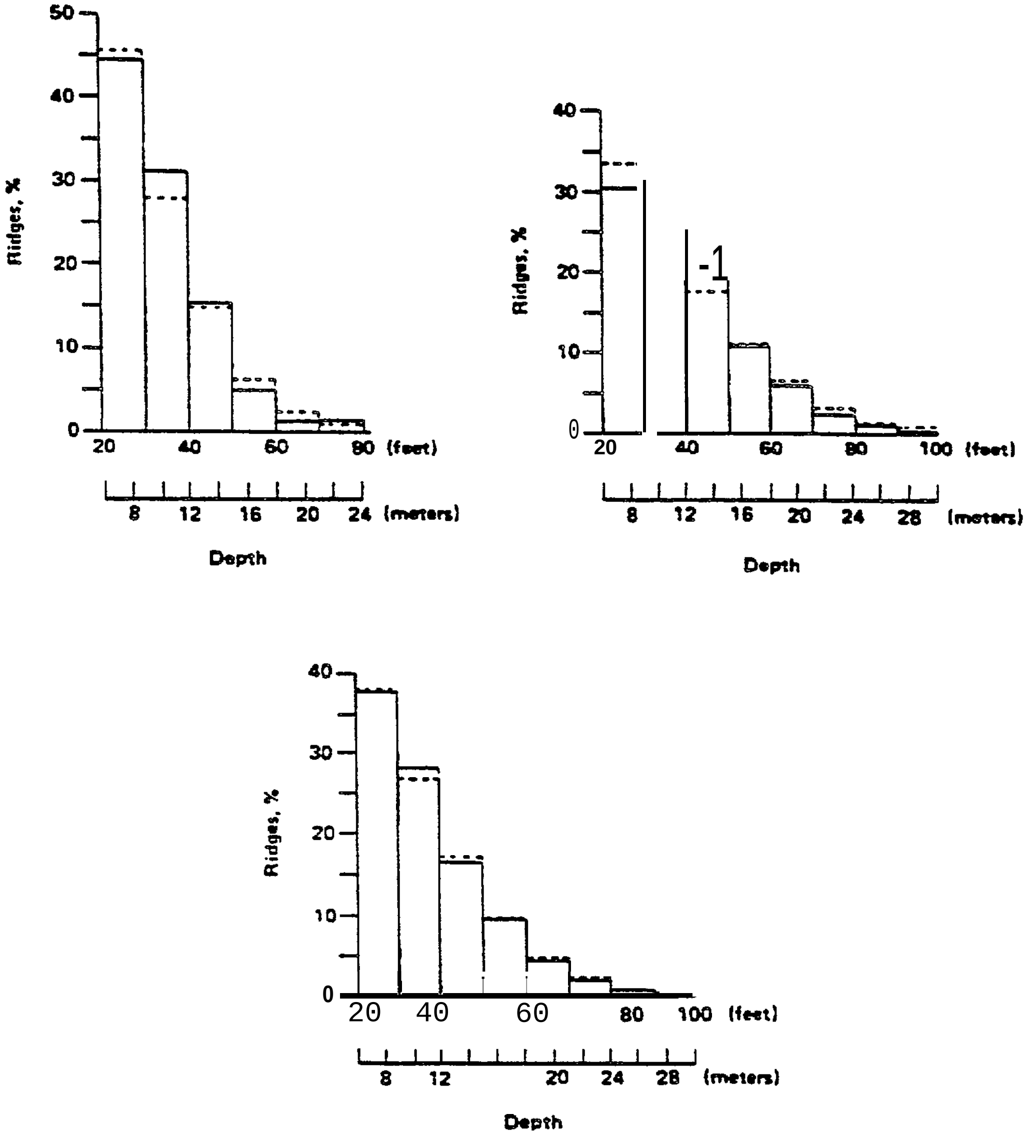
Figure 3.1-16. Pressure ridge height versus block thickness.

water. If, soon after formation, the solidifies of sail arid keel 'are similar ($k_f = k_d = 0.7$), then a sail height/keel depth ratio of 1/6.9 would be expected. Making an allowance for subsequent ice growth in the keel by setting $k_d = 0.83$ increases the f/d ratio to 1/5.8. However, measurements of ridges have given ratios of 1/4.9, and the statistical study of the ratios as taken by laser profilometry for sails and sonar profilometry for keels (Kozo and Diachok, 1973) yielded 1/5. A recent study by Wadhams (1980) suggests that isostatic imbalance commonly exists, and the ridge is partially supported by the surrounding ice sheet.

The multi-year pressure ridges have been studied primarily by laser profilometry and sonar, which is unable to reliably discriminate between the two types of ridging. Some studies on specific ridges have included coring and have discriminated properly, as will be discussed below.

Multi-year ridges constitute the most obvious hazard for offshore operations in the Alaskan Beaufort Sea in water depths from 20 to 90 m (65 to 300 ft). However, they are, on the one hand, often overestimated in their effect upon structures, considering that (a) for most of the interactions, a buffer of annual ice will exist between the structure and multi-year features, and also between adjacent multi-year features, (b) multi-year ridges are embedded in multi-year floes, which have a large number of thin and/or weak regions which result in tensile splitting of floes under very moderate conditions of pack ice movement and stress, and (c) even large multi-year ridges embedded withinmulti-year floes have been observed to have natural cracks crossing them. Such fractures take place under conditions of the drifting ice pack, and under presumably relatively low geophysical stresses. On the other hand, there is certainly a finite probability that a multi-year ridge could be positioned adjacent to a structure, and that the pack ice upstream could be composed of multi-year floes which have been compressed together for a sufficient time so that annual ice and weak multi-year ice have already built into ridges, thereby enabling the pack ice stress to be great enough to cause the multi-year ridge to fail against the structure. In this case, its geometry and properties become important and deserve discussion.

In Figure 3.1-17, the distribution function of multi-year ridge keel depths is given based upon laser profile and sonar data (Hibler et al., 1972; Hibler, 1975). Figure 3.1-18 illustrates the distribution function of multi-year ridge sail heights from the same source. Both keels and sails fit exponential distribution functions. Keel depths of 30 m (100 ft) have been observed and in considering the most extreme keel depth, one candidate certainly is the keel which produced the seabed gouge observed by Reimnitz et al. (1984) in 64 m (210 ft) water depth in the Beaufort Sea although this gouge may have been caused when the seabed was much lower. Reports of extreme multi-year keel depths of up to 47 m (154 ft) (Lyon, 1967), based upon submarine sonar data, are consistent with that observations but



HISTOGRAMS OF KEEL DEPTHS IN THE OFFSHORE PROVINCE
ALONG THE NORTH SIDE OF THE CANADIAN ARCHIPELAGO

Source: Hibler et al., 1972; Hibler, 1975

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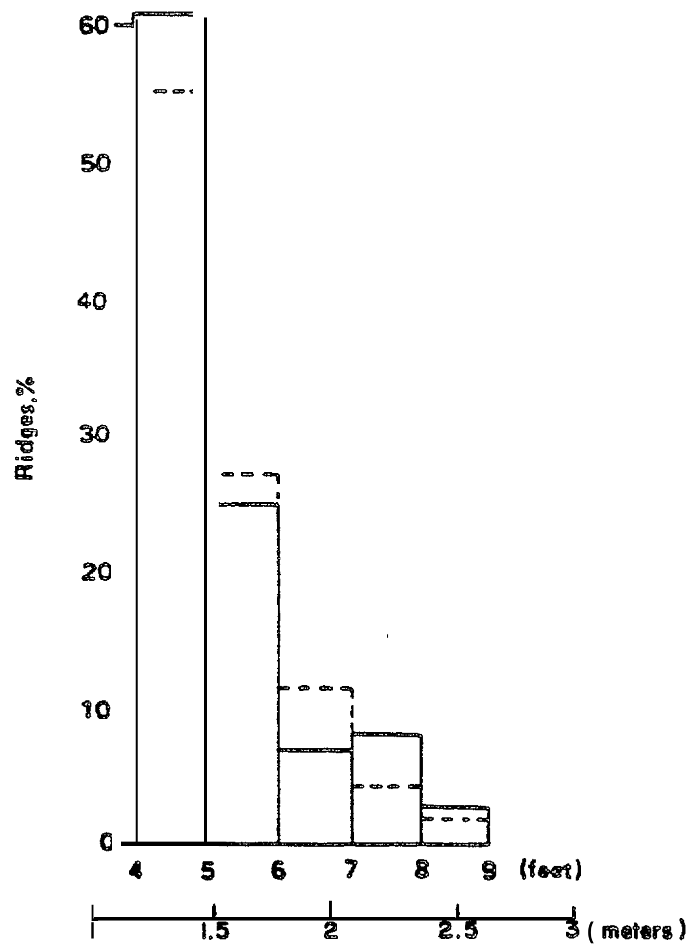
Figure 3.1-17. Histograms of pressure ridge keel depths.



HISTOGRAM OF RIDGE SAIL HEIGHTS IN THE SOUTHERN BEAUFORT SEA
NORTH OF THE U.S.-CANADIAN BORDER

Source: Hibler et al., 1972; Hibler, 1975

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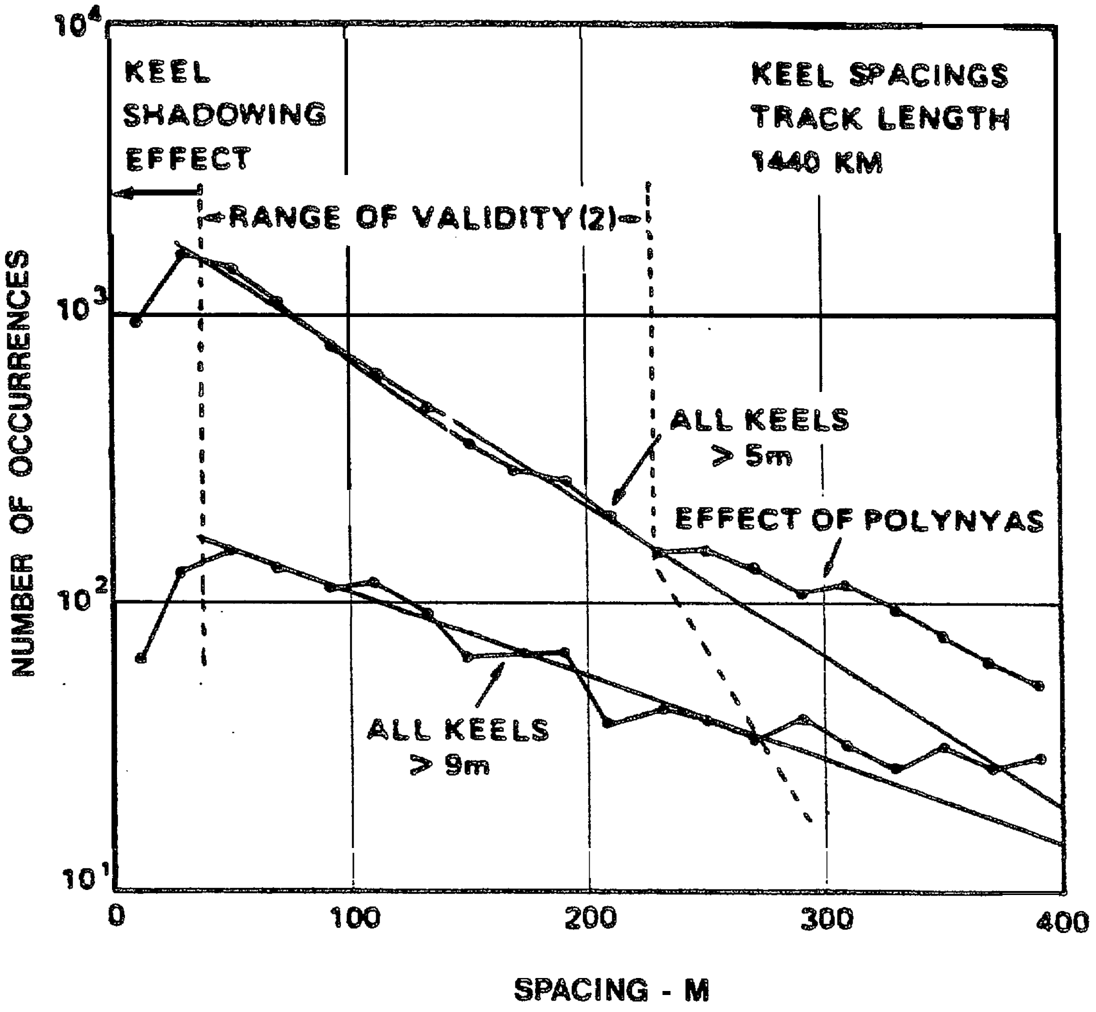
Figure 3.1-18. Histogram of pressure ridge sail heights.

the significance of such great keel depths is dubious because the mechanically germane parameter is the depth below the water surface to which the ridge has become fully consolidated. This will be discussed in more detail below.

The distribution function for the spacings between ridges has been presented by Hibler et al. (1972). It is important to note that the distribution function depends on the minimum ridge height selected and the relationship is logarithmic, i.e., the number of ridges greater than 1 m (3 ft) may be double the number greater than 1.3 m (4 ft). This point will have a significant effect on the performance of ships. The orientation of pressure ridge directions is very close to random, according to a study by Mock et al. (1972). More recent results by Wadhams and Home (1980) on the distribution of multi-year keel spacings show appreciable numbers of keels over 9 m (30 ft) deep, and the keel statistics produced by Leshack show appreciable numbers greater than 15 m (50 ft) deep. The results of Wadhams and Home (1980) are given in Figure 3.1-19. The lengths of multi-year ridges have been studied by Hibler and Ackley (1973) who applied the criteria that only ridges higher than 1.5 m (5.0 ft) were considered, and a ridge which dropped below 1 m (3.3 ft) and remained there for 100 m (330 ft) was ended. Their result is shown in Figure 3.1-20. Whether there is a correlation between the length and the thickness for very large ridges remains to be determined, but such a study would be difficult as the keels are not usually surveyed over the entire length and width of the ridge. A relationship has been



Distribution of keel spacings over whole submarine track. Bin size 20 m. Results are plotted for keels deeper than 4 m and 9 m, and a straight line is fitted to the central portion of each curve.

Source: Wadhams and Horne, 1980

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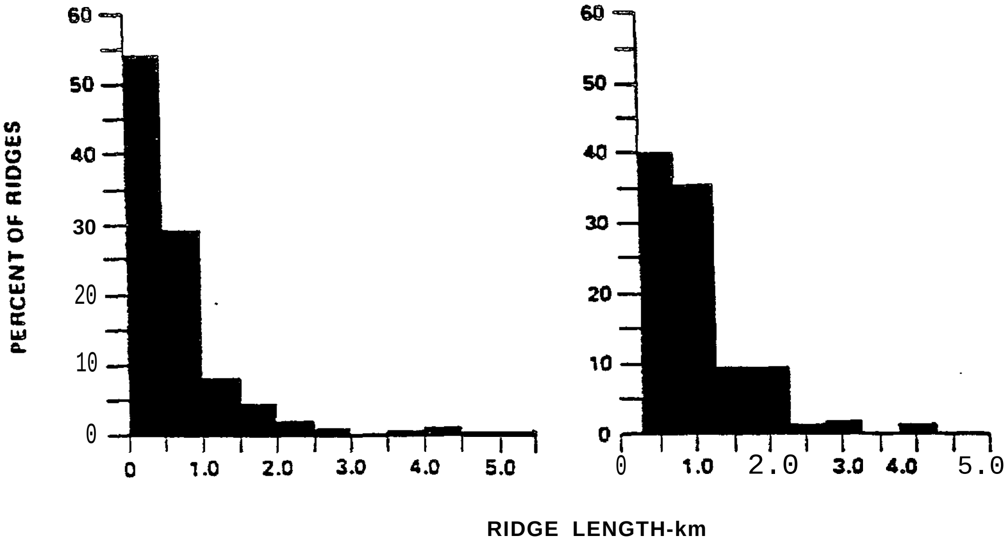
Figure 3.1-19. Distribution of pressure ridge keel spacings.



Distribution of pressure ridge lengths obtained (left) near the March 1971 AIDJEX camp (75°N, 131°W) and (right) near the March-April 1972 AIDJEX camp (75°N, 145°W) in the Beaufort Sea. Total number of ridges in the samples were 180 and 307, respectively.

Source: Hibler and Ackley, 1973

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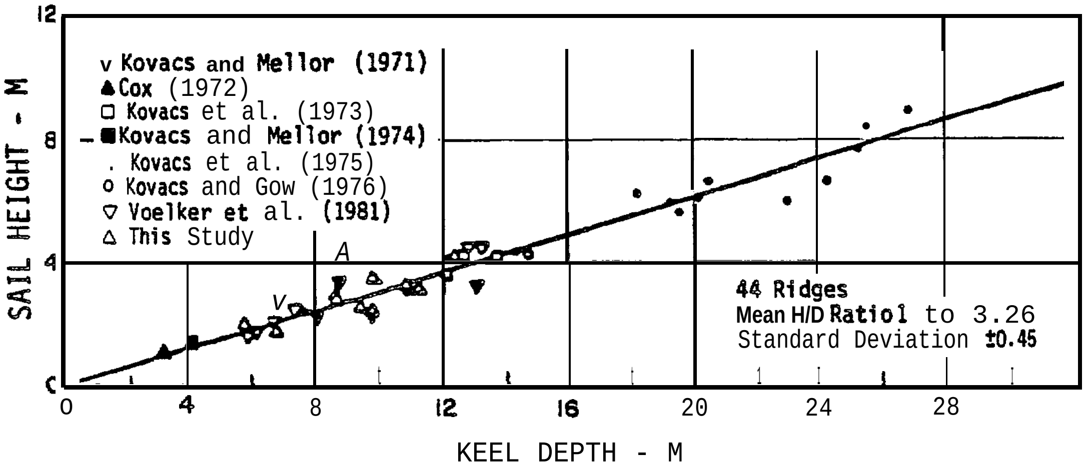
**Figure** 3.1-20. Distribution of pressure ridge lengths.

*presented* by Kovacs(1983) *between* multi-year ridge sail height and keel depth and is given in Figure 3.1-21. The mean ratio is 1/3.26 + 0.45. The data are from 44 ridges in the Beaufort and Chukchi Seas. The slope angle of the sail averages about 20°, and the slope angle of the keels average about 30°. A variety of cross-sectional profile variations are possible, but they all seem to have relatively flat-bottomed keels, which is to be expected when one considers the dynamics of formation of the multi-year ridge.

The formation processes involved in the multi-year ridge are extremely important because they are responsible for the size, composition, and hence the strength of the old ridge (Parameter and Coon, 1973). During the first summer melt season, the presence of heat input at the surface of the ridge warms the blocks of annual ice, and when they reach a temperature range of -7°C to -2°C, the brine inclusions within the ice become interconnected and the brine drains downward because of gravitational forces. This dense saline brine proceeds to mix readily with the sea water in the ridge voids below the water line. Later in the summer, the remaining crystals of virtually fresh ice at the top of the ridge begin to melt, supplying very low salinity water which drains downward to fill the brine channels to some degree, although there will still be air trapped in some regions of the ridge as fresh water drains downward to fill the spaces between blocks. The fresh water freezes when it reaches the 0°C isotherm, a region somewhere within the ridge. As the 0°C isotherm moves slowly downward in the ridge during the melt season,



Source Kovacs, 1983

BASED ON MEASUREMENTS OF 44 MULTI-YEAR
PRESSURE RIDGES IN THE BEAUFORT AND CHUKCHI SEAS

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Figure 3.1-21. Relationship between pressure ridge sail height and keel depth.

the spaces and channels available for the draining fresh water to drop through, and subsequently to freeze into, are gradually reduced. If the fresh water proceeds below the sea-water-line, it will remain unmixed on top of the sea water and freeze there. This progression of melting of fresh ice at the top of the ridge, and draining of the water to the 0°C isotherm, continues during the subsequent years of summer melting. Thus, the voids of the upper part of the keel are gradually filled with fresh ice, while the sea water temperature below the ridge remains very nearly -1.8°C.

As several summer melt seasons take place, additional conditions operate to bring the system into equilibrium. First, there is the reduction in the number of available pore spaces for the fresh water to drain vertically. Ultimately the pores will all be filled with fresh ice, forcing lateral drainage of ridge sail melt water into adjacent melt ponds on the surface at a slightly lower elevation. Second, as melt water does go under the ice into the voids of the ridge keel, it will tend to spread laterally before it freezes, creating a wide zone of consolidated fresh ice in the keel. This may become wider than the original keel, and it is difficult to see how a very deep keel of unfrozen blocks could become consolidated with this lateral spreading of fresh water taking place, as there is no way to confine the fresh water into the region of the very deep unconsolidated blocks of a deep keel. Third, there is a constant temperature in the core of the very old multi-year ridge, corresponding to the average annual temperature of the region. The seasonal temperature transients are damped out at a depth of the order of 10 m (33 ft) below the surface, meaning that the core of the ridge will remain at a temperature below 0°C during the entire year. In fact, there is also a transient phase lag in the penetration of a summer impulse of heat into the core of a ridge, so that the warm temperatures cannot arrive in the core of the ridge (once convection of meltwater is negligible) until later in the summer, at which time the source of meltwater from the upper surface is no longer available. This implies that there is a limiting depth within a very old multi-year ridge, beyond which the keel will *no* longer be consolidated.

In a very old ridge, the penetration of cold from above at a very gradual rate (because of the great thickness) will give rise to the formation of thin layers of new sea ice at the bottom of the fresh ice consolidated region. This will be of low strength, because of its temperature of -1.8°C. The unconsolidated blocks below this level will have very low strength as well, but may make the interaction with a structure more complicated because of their very presence when they ride up onto a cone, for example. It thus would be instructive to look for multi-year ridge salinity data where a layer of sea ice is found at the bottom of the consolidated region; this would be an indicator of the maximum possible thickness of consolidation of a ridge, which is an extremely important parameter for ice force calculations. In the data presented by Kovacs (1983), this takes place between 5.5 and 7 m (18 and 23 ft). An examination of the data presented by Voelker et al. (1981) from the Polar Sea cruise indicates consolidated thicknesses of from 5 to 12 m (16 to 40 ft). The 1982 cruise was in the Bering Sea and did not encounter multi-year ridges, but the 1983 cruise results found consolidated depths from 3 to 8 m (9 to 26 ft) (Voelker et al., 1983). On the basis of the 28 ridges thus examined, it appear's that a maximum consolidated thickness of 12 m (40 ft) for a multi-year ridge is a reasonable value for purposes of structure design. Such a level of consolidation could be present for structures in the 20 to 90 m (65 to 300 ft) water depth range.

The size of multi-year floes would be an important parameter if it were not for their inherent weakness. Large floes are likely to break along regions of weakness and cannot concentrate pack ice stress over their entire width (as it is measured in a region devoid of interaction effects). A study by Dickens (1979) showed floe sizes ranging from 0.5 to 10 km (0.3 to 6 mi) in the Beaufort Sea. Analysis of SLAR images by Weeks et al. (1982) showed circular multi-year floes (approximately) with diameters from 3.6 km (2 mi) to below 500 m (1600 ft). The distribution function was a negative exponential function.

An additional type of multi-year ice which deserves consideration is the multi-year hummock fields which form in the vicinity of the coast of Prince Patrick Island and M'Clure Strait (Wadhams, 1983). This region is characterized by a predominantly compressive motion of the ice of the Beaufort Gyre towards the shoreline. Multi-year ice floes as described above, which have multi-year ridges embedded within them, form grounded rubble fields along that coast, the block sizes of which can be very large. Subsequent melting and refreezing of fresh meltwater within these rubble fields can lead to consolidated masses of ice which may be thicker than the 12 m (40 ft) mentioned above; unfortunately no data have been published on the thickness of this category of ice, even though it eventually will free itself from the seabed and join in the motion of the Beaufort Gyre.

For preliminary design purposes, the following ice ridge characteristics have been used:

| Annual Ice | EXPLORATION | PRODUCTION |
|---|---|---|
| Sail height | 4 m (13 ft) | 6 m (20 ft) |
| Keel depth | 20 m (66 ft) | 30 m (98 ft) |
| Consolidated thickness | 2.5 m (8 ft) | 3.5 m (12 ft) |
| **Multi-year Ice** | | |
| Sail height | 3 m (10 ft) | 4 m (13 ft) |
| Keel depth | 20 m (66 ft) | 30 m (98 ft) |
| Consolidated thickness | 8 m (26 ft) | 12 m (40 ft. ) |

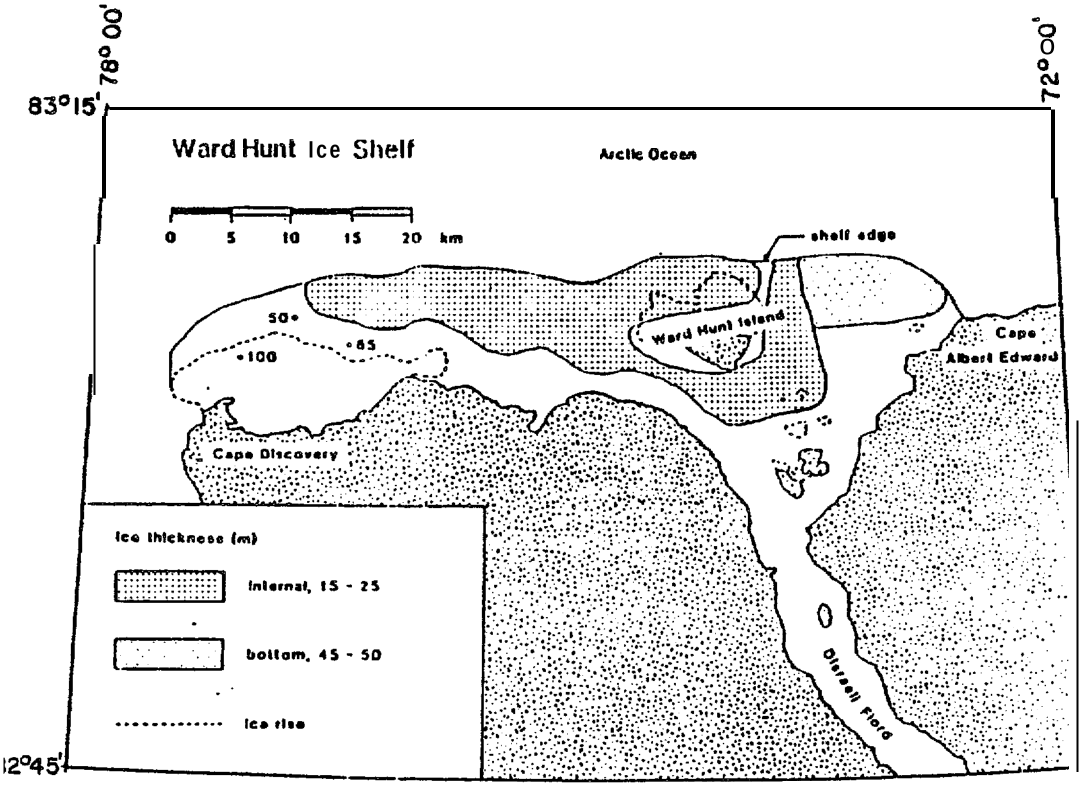
## e Ice Islands

Ice islands are extremely large pieces of onshore ice shelves that break off (calving) and drift within the Beaufort Gyre. The existence of ice islands has been known since the early exploration of Parry (1821), who described an immense floe in M'Clure Strait which "was covered with large hummocks, giving to its upper surface the appearance of hill and dale...". Greely (1886) notes one sighting near Cape Baird in August 1883, an immense floe "fifteen miles long and of unknown width." In 1918 Storkerson and four others drifted for six months on an ice floe in the Beaufort Sea that was "a large island of ice about seven miles wide and at least 15 miles long." A thorough search of RCAF aerial photos (Greenaway, 1952) yielded 59 possible ice islands as well as many more smaller fragments. Both Pelham Aldrich of the Nares Expedition (1875-76) and Peary (1907) traversed the ice shelves of Ellesmere Island, including the Ward Hunt Ice Shelf, and reported the long, prairie-like swells of its surface (Dunbar, 1952). On August 14, 1946, the ice island T-1, measuring about 28 by 33 km (17 by 21 mi), was discovered about 550 km ([illegible]0 mi) north of Point Barrow. Ice island T-2, discovered in 1950, had a size of 32 by 33 km (20 by 21 mi). On July 29, 1950, the ice island T-3 was discovered, measuring 8 by 17 km (5 by 10 mi). The most recent sighting of T-3 was in July 1984, just west of Julianahab, Greenland, indicating that it had finally been ejected from the Arctic Ocean in 1984 after at least three known circuits of the Beaufort Gyre. In 1962, five ice islands were produced by calving from the Ward Hunt Ice Shelf, totaling 600 km$^2$ (230 mi$^2$) of ice area. A review of these and many more events can be found in Sackinger and Stringer (1983) and Sackinger et al . (1984).

Unlike the multi-year floes, the ice islands seem to be of rather uniform composition and thickness, although little data are available to support this suggestion. The ice islands which originate from the Ward Hunt and Milne Ice Shelves can be expected to have a thickness of up to 50 m (165 ft), similar to that of the outer edge of these shelves. In Figures 3.1-22 and 3.1-23, the results of Prager (1983) show thickness distribution of the two ice shelves. According to Jeffries (1984), these ice shelves have salinity profiles with depth which vary considerably depending upon location. However, freshwater ice and old sea ice or brackish ice are quite typical in layers and salinity values from zero to about 4 ppt are to be expected.

The mechanical properties of the ice will vary with depth, because of the salinity layering, and because of the temperature variation with depth. The linear temperature gradient from the ocean (-1.8°C) to the center portions of the shelf (about -13°C) are relatively unaffected by seasonal changes, with only the top 3 m (10 ft) changing temperature with the seasons. The details of the ice shelves represent an immensely complex subject which is currently being researched by Jeffries (1983a, 1983b, 1983c) and Serson.

It is the opinion of this study team that although the



Ice-layer thickness of the Ward Hunt Ice Shelf. Included are three spot-depths over the Cape Discovery ice rise. The eastern part where a clear bottom echo at 45-50 m depth was observed may need to be displaced towards Cape Albert Edward.

Source: **Prager,1983**

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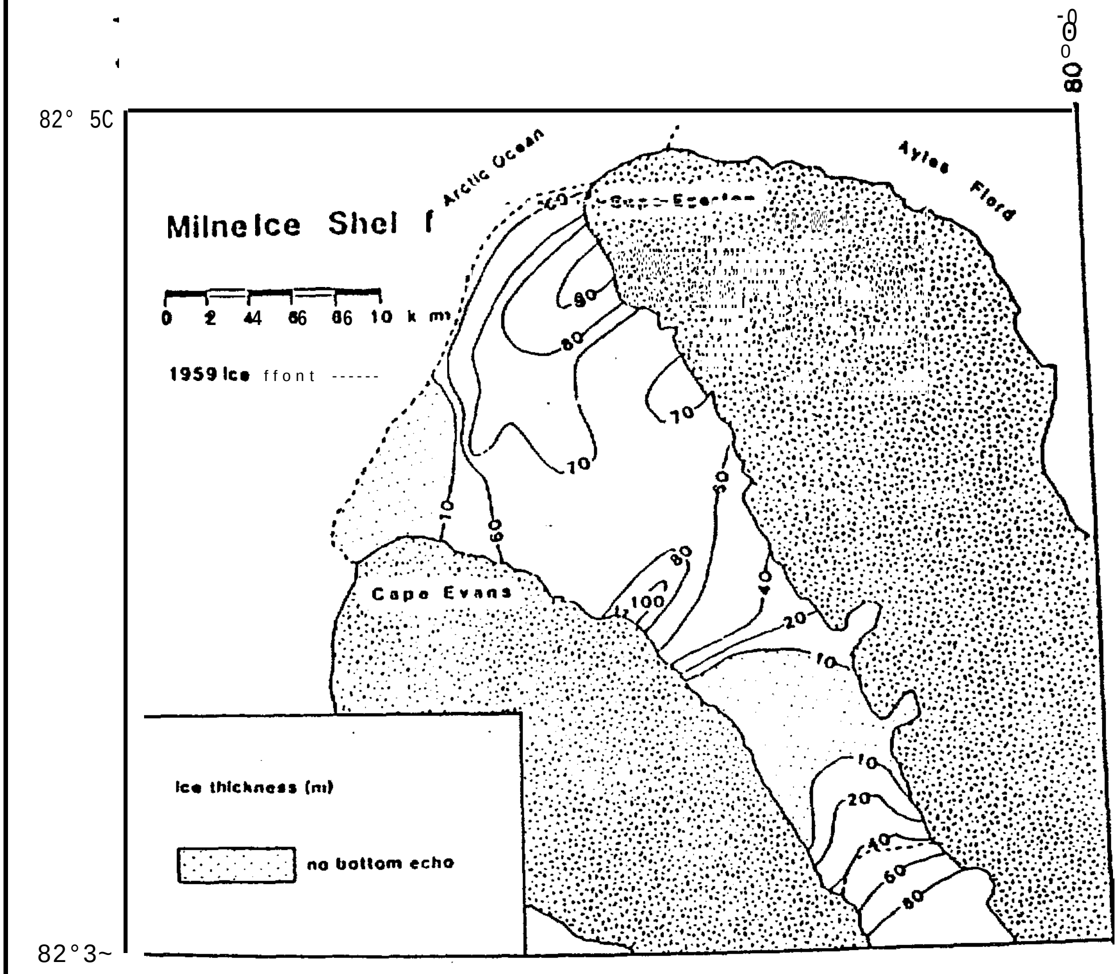
**Figure** 3.1-22. Ice thickness map of the Ward Hunt Ice Shelf.



Source: Prager, 1983

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Figure 3.1-23. Ice thickness map of the Milne Ice Shelf.

probability of encounter of an offshore structure and an ice island is vet-y small, it may not be negligible during the life of a production structure, and it must be considered in the offshore development process. Research is in progress to define the probability of encounter (Sackinger et al., 1984; Sackinger and Stringer, 1983) to permit a rational evaluation of development alternatives.

### f) Ice Coverage and Concentration

Ice concentration and pack edge location are important parameters in the assessment of trafficability for both construction and exploration activities. There exists a high year to year variability in ice edge extent, as well as a variation from week to week caused by the movement of storm tracks through the Beaufort Sea region. Therefore, neither the ice edge extent nor the open water duration period can be accurately predicted for any given year (LaBelle et al., 1983; Brewer et al., 1977).

The Bering Sea is normally free of sea ice by early summer, and as summer continues the ice edge retreats northward into the Chukchi Sea. At the same time, the ice concentration in the area north of Canada between Mackenzie Bay and Amundsen Gulf begins to decrease. The ice edge usually continues to retreat northward in both areas and eventually merges into one continuous edge, reaching a maximum northward position during the latter half of September. Hence, the

Beaufort Sea study region experiences the least open water window period in the area from the Chukchi to Canadian Beaufort Seas. Most years an ice-free channel near shore allows ships to pass around Pt. Barrow to Mackenzie Bay. Sometimes the ice edge does not retreat far from the coast, and belts or patches of ice may break from the main pack and pose a hazard to vessels. During fall, beginning in October, the pack edge reverses direction and begins to move southward. Mean ice drift during October and November is from Alaska toward the Soviet Union.

From source information covering a 29-year period, 1953 through 1981, Webster (1982) determined the ice edge location for the first and fifteenth of each month (LaBelle et al., 1983). This information is shown on Figures 3.1-24 through 3.1-29. Some adjustments had to be made due to inconsistencies in data from different sources and the fact that observation dates were not always on the first and fifteenth of the month. Aircraft observations were deemed better than satellite data. Often the displayed data are averages of data recorded from several sources. On the maps the empirical probabilities are given in 25 percent increments with the 0, 50, and 100 percent probability isopleths depicting, respectively, the extreme southerly, the median and extreme northerly position of the ice edge.

Of major importance to the planning of construction and supply transportation activities is the knowledge of when the ice conditions

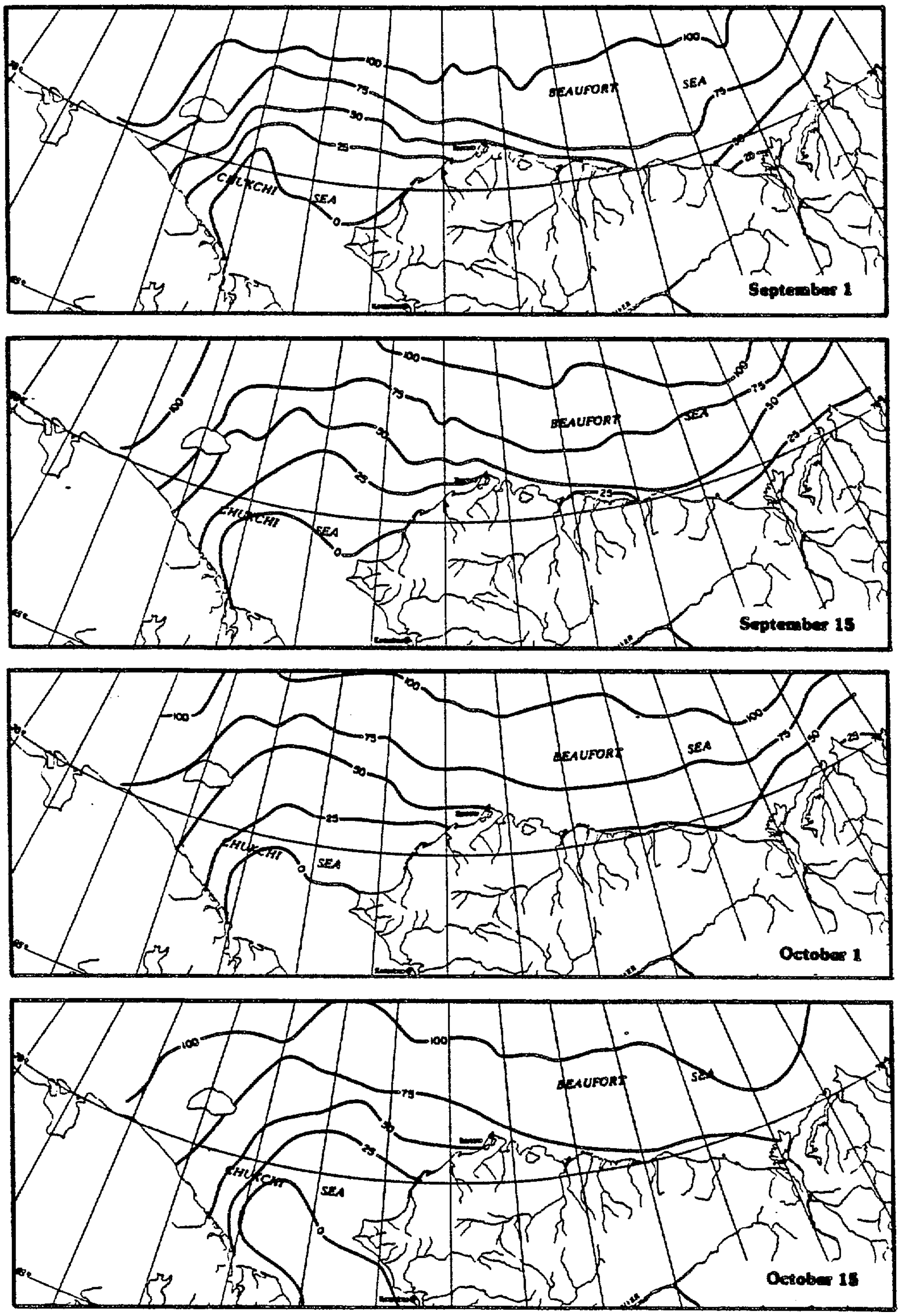

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Figure 3.1-24. Ice edge location probabilities, in percent, September and October.

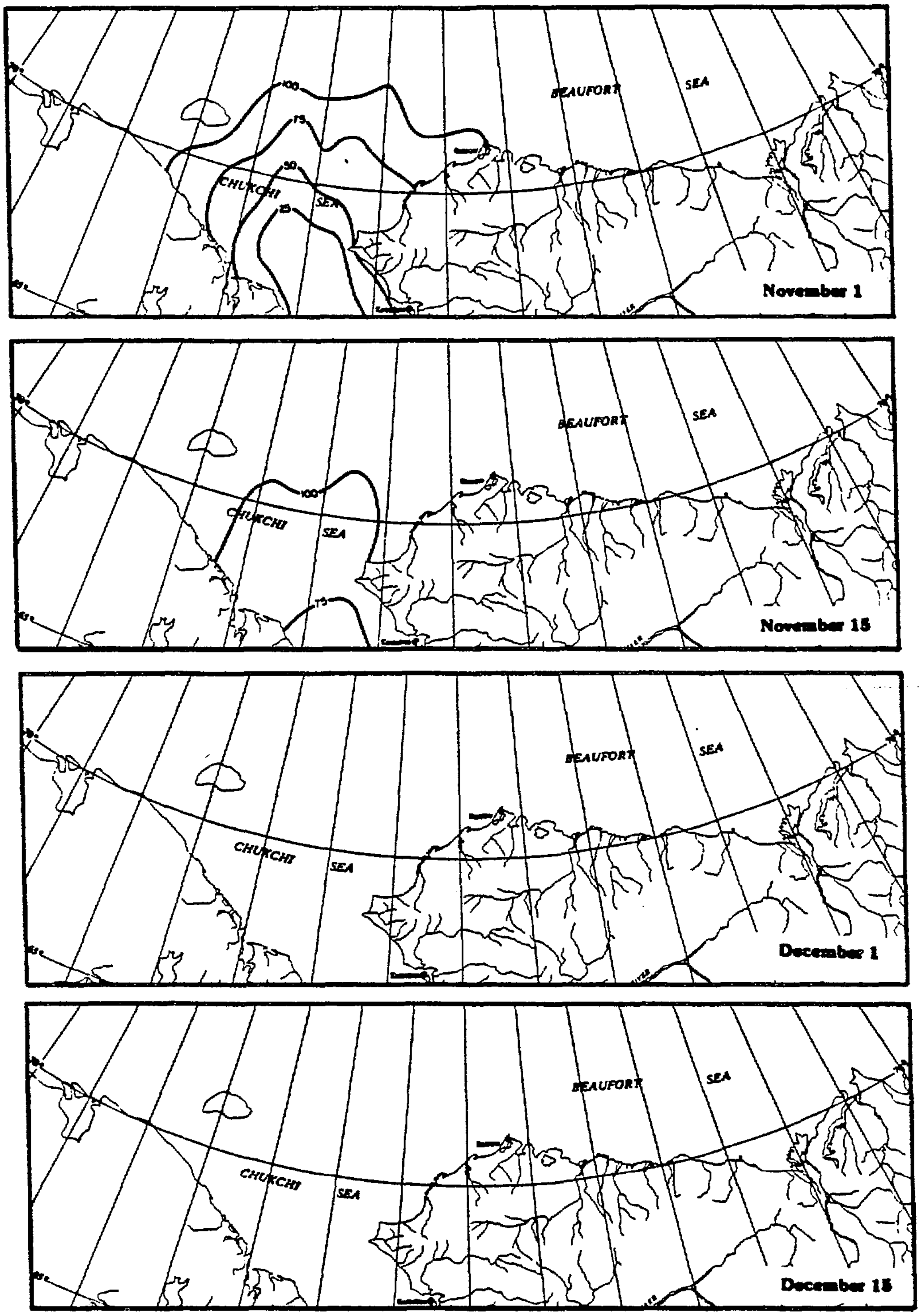

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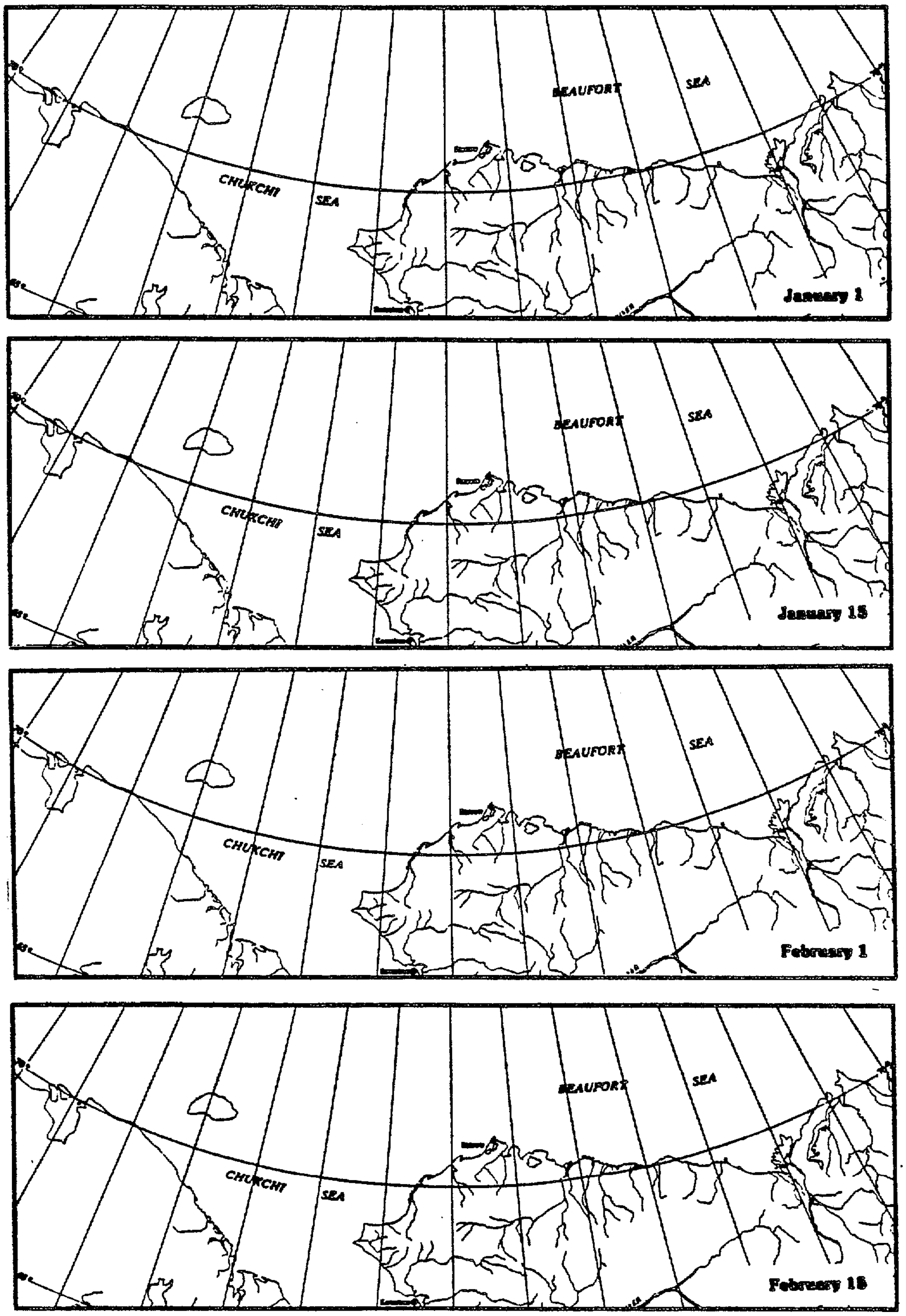
Figure 3.1-25. Ice edge location probabilities, in percent, November and December.



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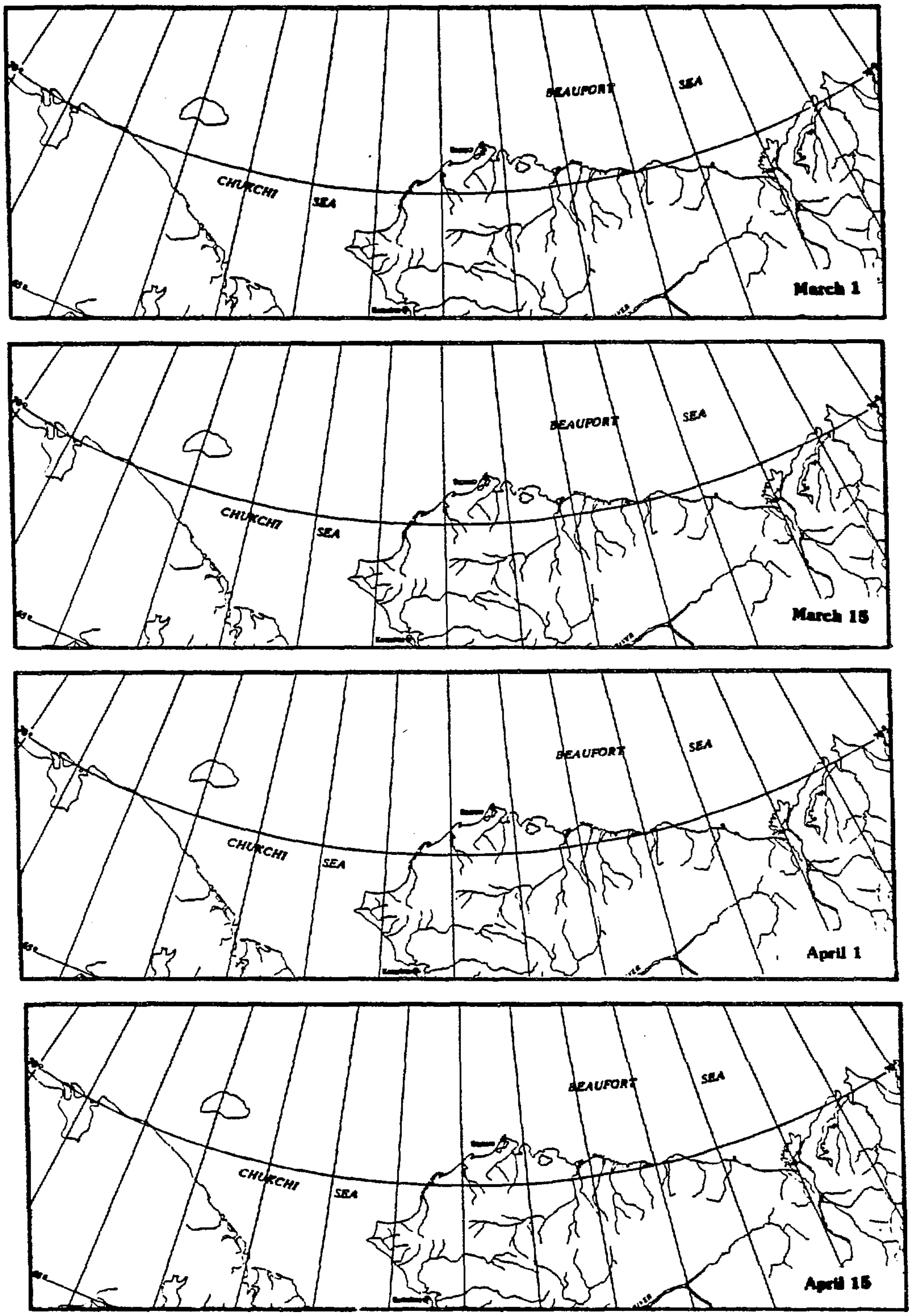
Note: 100% for entire region

Figure 3.1-26. Ice edge location probabilities, in percent, January and February.



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Note: 100% for entire region

Figure 3.1-27. Ice edge location probabilities, in percent, March and April.

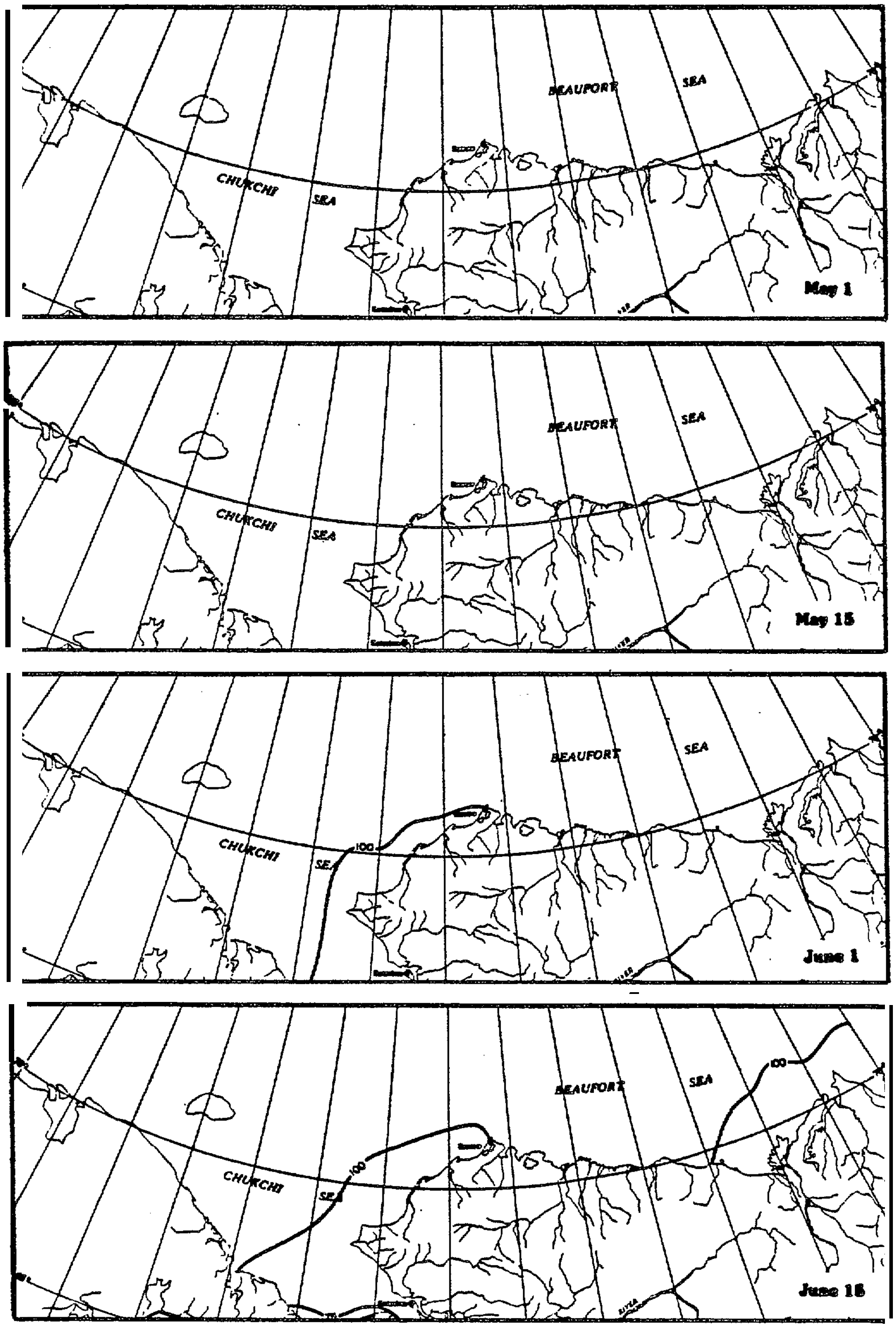

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Figure 3.1-28. Ice edge location probabilities, in percent, May and June.

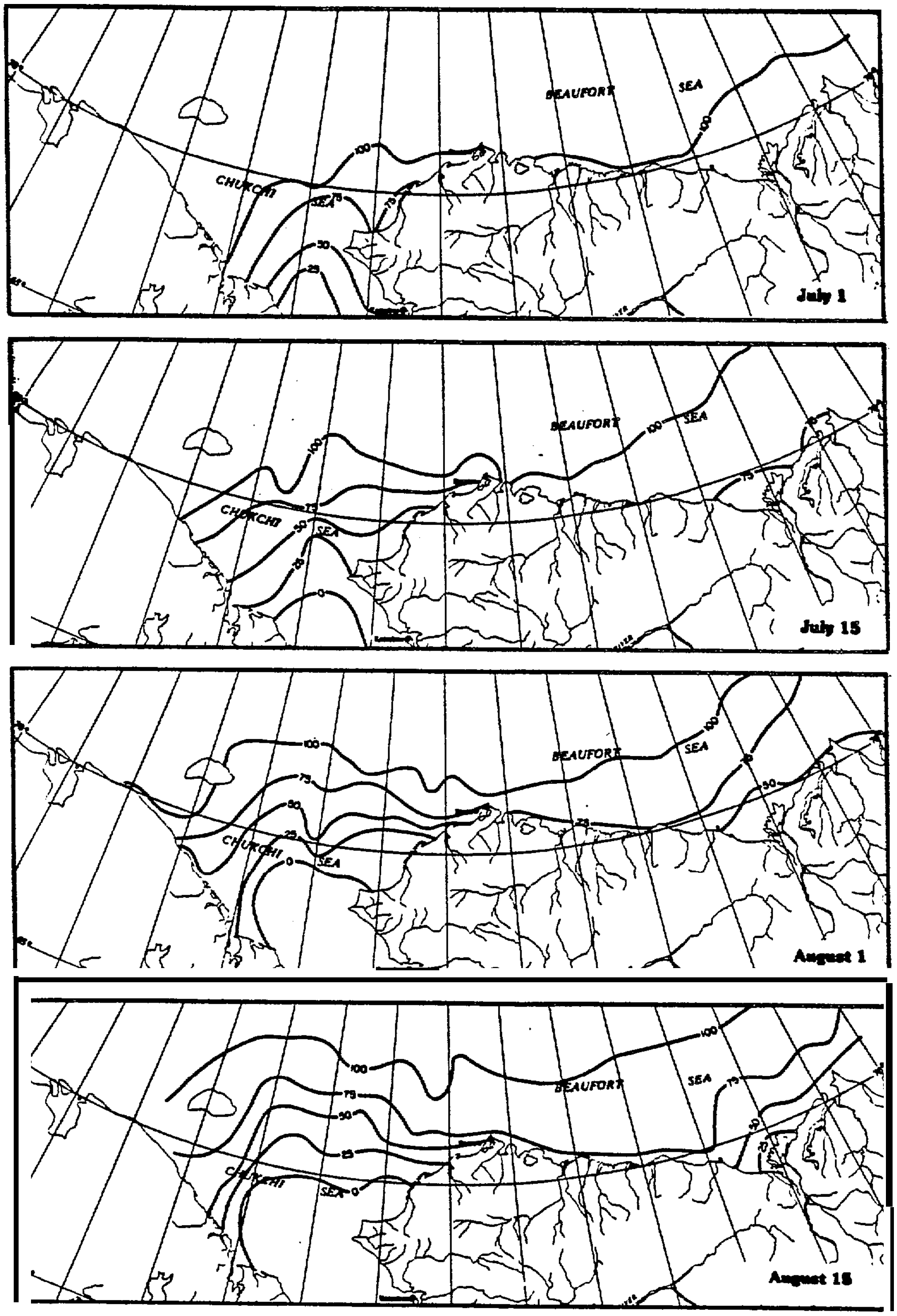

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Figure 3.1-29. Ice edge location probabilities, in percent, July and August .

will permit ships or towed structures to move northward through the Bering Strait and on around Point Barrow to locations along the north coast of Alaska. Figure 3.1-30 was prepared by the U.S. Navy's Fleet Weather Facility at Suitland, Maryland. It summarizes the ice conditions along the route from Point Barrow to Prudhoe Bay for each year from 1953 to 1975. The earliest date on which the sea route has had four oktas or less ice coverage was July 19, and during the 1975 season, four oktas or less did not occur at all.

A study carried out by Wilson (1977) concluded that a vessel with a 12 m (40 ft) draft would have a greater than 95 percent probability of being able to complete a one way voyage from the Pacific to MacKenzie Bay in any year.

### g) Ice Drift Velocity

In the region of the pack ice edge, during the summer months, drift velocities of isolated floes or groups of floes along the free edge of the pack can be as great as 0.8 to 1 m/s (2.6 to 3.3 fps). However, this situation is one in which an appreciable amount of open water and melting annual ice is available during the interaction with a structure, so that the impact forces on a structure would not be extremely high. On the other hand, when the winter pack is moving around a structure, the ice coverage is nearly 100%, and there is a system of cracks which form over distances of the scale of 10 to 100 km (6 to 60 mi). These cracks contribute to the details of floe size

| | Severity Rank | Year* | 1 nmi | 2 nmi | S nmi | 4 nmi | 5 Date | 6 Date | 7 ● DSVS | 8 ● Daya |
|---|---|---|---|---|---|---|---|---|---|---|
| Mildest | 1 | 1958 | 50 | 150 | 50 | 210 | 7/19 | 10 ·25 | 92 | 99 |
| | 2 | 1968 | 25 | 165 | 30 | 200 | 7/19 | 10/18 | 86 | 91 |
| | 3 | 1954 | 20 | 115 | 20 | 210 | 8/01 | 09 '30 | 38 + | 61 + |
| | 4 | 1973 | 5 | 80 | 5 | 190 | 7/31 | 10/20 | 73 | 82 |
| | 5 | 1962 | 25 | 150 | 30 | 150 | 7/19 | 09/30 | 49+ | 68 + |
| | 6 | 1%3 | 5 | 130 | 5 | 130 | 8/13 | 10/18 | 67 | 67 |
| | 7 | 1961 | 15 | 105 | 15 | 135 | 7/25 | 09/'24 | 49+ | 62+ |
| | 8 | 1979 | 0 | 125 | 0 | 125 | 8/04 | 10/08 | 31 | 56 |
| | 9 | 1974 | 10 | 100 | 10 | 100 | 8/06 | 10/05 | 35 | 61 |
| | 10 | 1959 | 20 | 65 | 20 | 65 | 7/19 | 10/06 | 42 | 86 |
| | 11 | 1972 | 0 | 60 | 30 | 90 | 7/31 | 10/01 | 45 | 63 |
| | 12 | 1978 | 5 | 70 | 30 | 95 | 7/25 | 10/09 | 35 | 76 |
| | 13 | 1977 | 5 | 55 | 25 | 85 | 8/02 | 10/15 | 63 | 74 |
| | 14 | 1957 | 5 | 45 | 70 | 60 | 8/01 | 10/'06 | 18 | 67 |
| | 15 | 1981 | 0 | 0 | 35 | 100 | 7/26 | 10/'01 | 0 | 66 |
| | 16 | 1%7 | 15 | 0 | 30 | 50 | 7/25 | 10/12 | unknown | 68 |
| | 17 | 1966 | 5 | 0 | 5 | 45 | 8/01 | 10/22 | 24 | 65 |
| | 18 | 1%5 | 0 | 10 | 0 | 70+ | 8/25 | 09/25 | 25 | 32 |
| | 19 | 1980 | 15 | 25 | 15 | 25 | 8/05 | 09/30 | 11 | 42 |
| | 20 | 1953 | 0 | 0 | 5 | 35 | 7/27 | 09/16 | 5 | 52+ |
| | 21 | 1976 | 0 | 15 | 0 | 15 | 8/15 | 10/07 | 21 | 53 |
| | 22 | 1971 | 0 | 0 | 0 | 30 | 8/23 | 11/01 | 8 | 71 |
| | 23 | 1%0 | 0 | 0 | 20+ | 20 | 8/05 | 09/07 | o ' | 34 |
| | 24 | 1964 | 0 | 0 | o | 5 | 8/13 | 09/20 | 0 | 39 |
| | 25 | 1970 | 0 | 0 | 5 | 0 | 8/06 | 09/14 | 0 | 32 |
| | 26 | 1956 | 0 | 0 | 0 | 40 | 9,07 | 09/30 | 0 | 24 |
| | 27 | 1969 | 0 | 0 | 0 | 30 | 9/07 | 09/18 | 5 | 12 |
| | 28 | 1955 | 0 | 0 | 5 | 15 | 9·13 | 09/24 | 0 | 12 |
| Most Severe | 29 | 19?5 | 5 | 0 | 5 | 0 | *never* | *never* | 0 | 0 |

Column I-Distance from Point Barrow northward to ice edge (10 August]
Column 2—Distance from Point Barrow northward to ide edge (15 September)
Column 3—Distance from Point Barrow northwad to boundary d five-tenths ice concentration (10 August)
Column 4-Distance from Point Barrow northward to boundary of five-tenths ice concentration (15 September)
Column S-initial date entire sea route to Prudhoe Bay less than/equal to five-tenths ice concentration
Column 6-Date that combined ice concentration and thickness dictate end d prudent navigation
Column 7-Number 01 days entire sea route to Prudhoe Bay ice-free
Column 8-Number d days entire sea route to Prudhoe Bay less than/equal to five-tenths ke

"'fears are listed in order d increasing severity based on parameters h columns 2.4.5.7, and 8.

Source: U.S. Navy Fleet Weather Faci 1 ity

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Figure 3.1-30. Summary of ice conditions between Point Barrow and Prudhoe Bay.

and velocity at the boundary of the structure, and the extended region of ice surrounding the boundary. An example of this kind of velocity field is found in the study by Stringer and Barrett (1975), who examined details of ice movement near the grounded ice feature at 160°W, 72°N, known as "Katie's Floeberg." In one case, ice velocity upstream of the floeberg was 17.8 cm/sec (0.58 fps), whereas closer to the floeberg it was 8 to 9.6 cm/sec (0.26 to 0.31 fps) and values from 6 to 9 cm/sec (0.2 to 0.3 fps) were obtained on another occasion. Values of velocity in this range can be taken as typical for winter shear zone interactions. It should be noted that these are average velocities taken over a 24 hour period, and the local instantaneous velocity may be higher. Instantaneous ice velocity measurements in the shear zone have been taken but the information is proprietary and no data have been published.

For preliminary design purposes, the following floe velocities have been used:

Open water (summer) 1.0 mps (2.0 knots)
Ice packed (winter) 0.15 mps (0.3 knots)

h) Ice Coefficient of Friction

The coefficient of friction between ice and the surfaces of an offshore structure is quite variable, as it depends upon the material, the surface roughness, the presence of coatings, the normal force, whether the interface is wet or dry, the temperature, and the velocity. Coefficient of friction data have been developed by Tusima and Tabata (1979) and Oksanen (1980) and additional data and analysis have been developed by Saeki et al. (1984). Coatings can be utilized to reduce the coefficient of friction of ice on steel surfaces. The Finnish coating, Inerta 160, is the most durable in icebreaker service, having a coefficient of 0.11 @ -10°C. The cases presumed applicable are for a wet interface between ice and structure.

For preliminary design purposes, the following coefficients of friction have been used:

| | |
|---|---|
| ice/steel | 0.15 |
| ice/concrete | 0.30 |

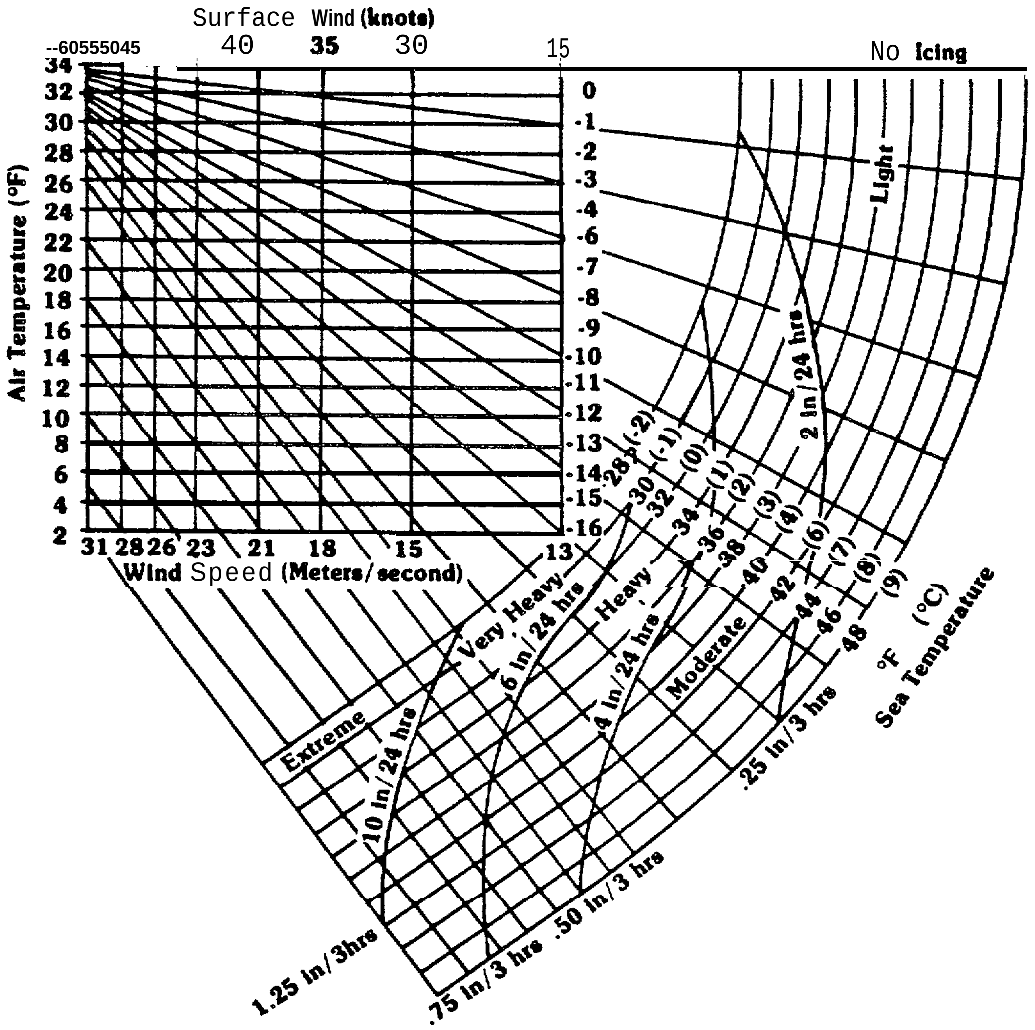
i) Superstructure Icing Rate

Icing on a structure at sea, particularly a floating structure, can be a severe hazard. Accretion of as much as 2.5 cm (1 in.) of ice in three hours time can lead to an extra gravity load of hundreds of tons. Most occurrences of known icing events in Alaska waters have occurred along the Gulf of Alaska coast, in the vicinity of Kodiak Island and in the southern Bering Sea (LaBelle, 1983). Offshore areas along the Beaufort Sea coast probably have conditions conducive to icing but virtually no vessels or structures were in the area after September. The prediction of the quantity of ice buildup is difficult. A nomogram for spray icing where the humidity is low (20 to 50 percent) is shown in Figure 3.1-31 (Wise and Comiskey, 1980).

Certain ranges of air temperature, water temperature, and wind speed must be met to cause significant accumulations of superstructure icing (l-aBelle et al., 1983). These conditions are (1) air temperature less than the freezing point of sea water, (2) wind speed of 10 m/s or more, and (3) seawater temperature colder than 8°C. The most common meteorological situation for icing, one which is common in the Alaskan Beaufort Sea, is to have wind blow from cold land or pack ice toward open water with a fetch sufficient to produce sizable waves and spray. Farther from the ice edge or shore the temperature of the air warms up to near the water temperature, so the chance of significant icing is lessened. If the cold air has low moisture content, icing can be more severe because the dry air has a greater capacity for absorbing latent heat of evaporation at the air-ice interface.

For preliminary design purposes, the following superstructure icing rate has been used:

Maximum icing rate 3.0 cm (1.2 in.) per3 hr



Categories

| Name | Rate Per 3 Hours |
|---|---|
| Light | .1" to .2s' |
| Moderate | .25" to .50" |
| Heavy | .s0" to .75" |
| Very Heavy | .75' to 1.25" |
| Extreme | 1. 2S" or more |

Source: Wise and Comiskey, 1980

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Figure 3.1-31. Icing nomogram.

### 3.1.2 Waves

The presence of waves in the Beaufort Sea is limited to the summer season because the entire region is covered by ice for the remainder of the year. Even during summer, wave heights are limited by the nearshore ice and islands which reduce the fetch.

Highest. wave heights can be expected to occur in September when the ice edge location is generally furthest north. Although prevailing winds are generally from an east to northeasterly direction throughout the region, high winds have been reported from the west and northwest as well.

API RP2A "Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms" (revisions underway) recommends a maximum wave height of 12 m (39 ft) and period of 11 sec for all water depths greater than 15 m (49 ft) in the U.S. portion of the Beaufort Sea. These values have been used for this study.

### 3.1.3 Water Depth

The geographic boundaries established for the study region include both areal extent (Diapir Field) and water depth. The study region, by definition, encompasses water depths from 20 to 90 m (65 to 300 ft) and such depths are present in the three study sectors (Western, Central and Eastern) as shown in Figure 1.2-2. All water depths are referred to mean lower low water (MLLW).

### 3.1.4 Winds

Winds in this region are quite persistent in both speed and direction. The prevailing winds throughout the region, based on observations at nearby coastal stations, are from an east to northeasterly direction, except in the vicinity of Barter Island, where westerly winds predominate during the winter months.

The maximum sustained wind (one minute average) for a 100 year return period was obtained from the "Climatic Atlas" (Brewer et al., 1977). One-hour average and three-second gust wind speeds were calculated based on well established procedures (Meyers et al., 1969).

For preliminary design purposes, the following wind speeds, at the standard elevation of 10 m (33 ft), have been used:

| | |
|---|---|
| Max. one-minute wind | 50 mps (97 knots) |
| Max. three-second gust | 60 mps (117 knots) |
| Max. one-hour wind | 40 mps (78 knots) |

### 3.1.5 Currents

Currents tend to be site specific and very little data are available on currents in the study area. The circulation during summer is strongly wind driven. As with prevailing winds, currents are predominantly from the east, but usually change to westerly during storms. Maximum surface currents have been taken from the Environmental Impact Statements for the Diapir Field (U.S.D.I., 1984, 1982, 1979) and bottom currents have been extrapolated from this information.

For preliminary design purposes, currents have been assumed to be parallel to the general trend of the bathymetry with the following speeds:

| | |
|---|---|
| Max. surface current | 1.0 mps (2 knots) |
| Max. bottom current | 0.25 mps (.5 knots) |

### 3.1.6 Tides/StormSurge

The tides appear to approach from the north and are generally mixed semidiurnal. Maximum diurnal tide ranges are obtained from the Climatic Atlas (Brewer et al., 1977).

Information on storm surges, which are increases in sea level above astronomical tide levels due to severe storms, is somewhat limited. Storm surges are generally maximum at the shoreline and decrease with increasing distance from shore. The storm surge for the study area has been estimated from the reported onshore maximum storm surge, as documented in the Climatic Atlas (Brewer et al., 1977).

For preliminary design purposes, the following water level variations have been used:

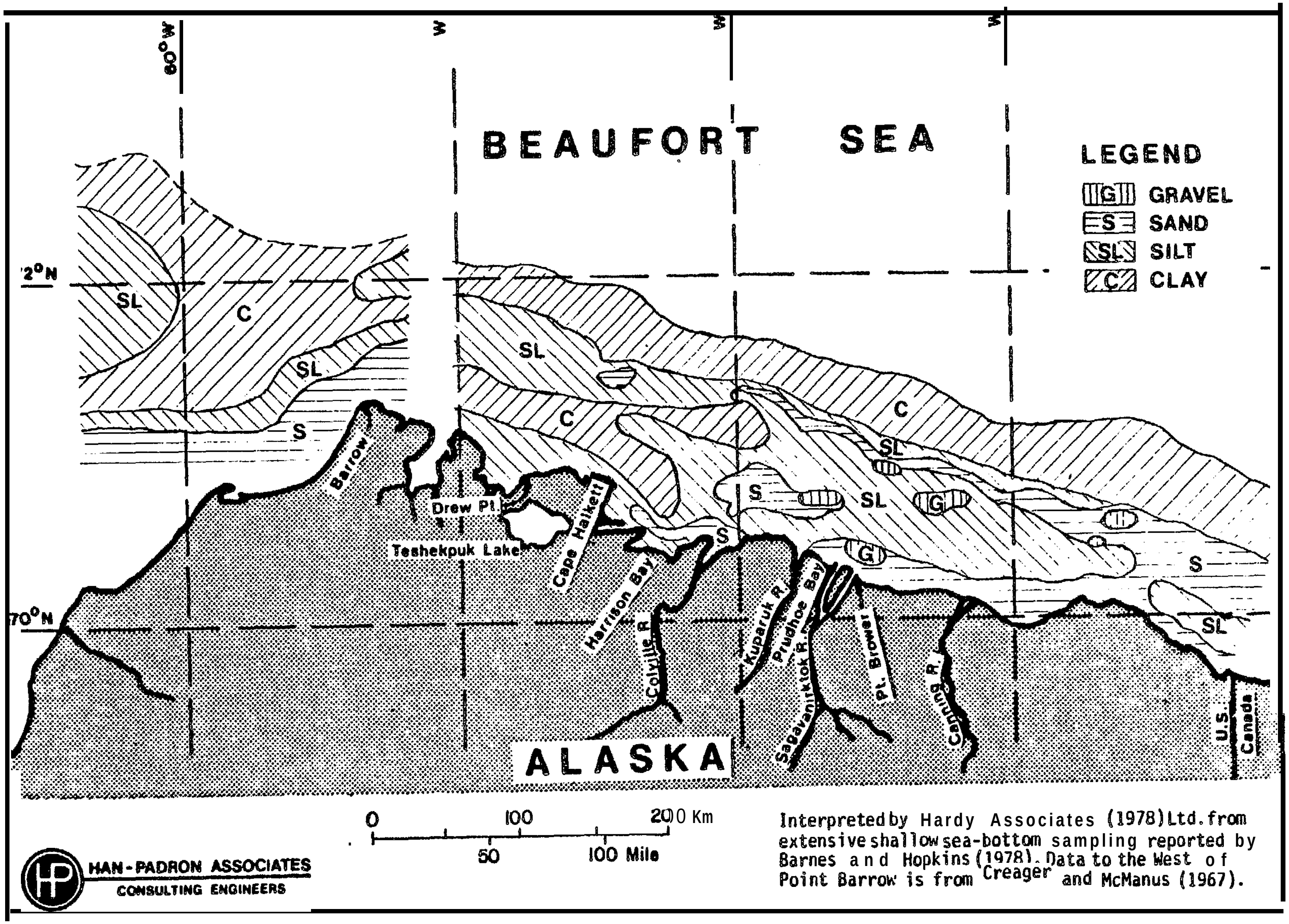
| | |
|---|---|
| Tidal range | 0.2 m (0.7 ft) |
| Storm surge | 2.0 m (6.5 ft) |

### 3.1.7 Geotechnical Conditions

In the years 1970-1973, extensive bottom sediment sampling was carried out by the U.S. Geological Survey within the study area. This sampling only penetrated the top few centimeters of the ocean sediments. These data are summarized on the map given on Figure 3.1-32, and reported by Barnes and Reimnitz (1974), and Barnes and Hopkins (1978).

The second primary source of geotechnical data is the 1976/77 U.S. Geological Survey offshore drilling program, which completed about eight drill holes over a distance of about 16 km (10 mi) offshore from Prudhoe Bay. This program delineated fine-grained soils 3 to 10 m (10 to 33 ft) in thickness, overlying coarser dense sands and gravels, interspersed occasionally with finer-grained sediments. All of the fine-grained sediments appeared overconsolidated, with high degrees of overconsolidation in the near-surface soils in shallow water areas. The overconsolidation, which gives

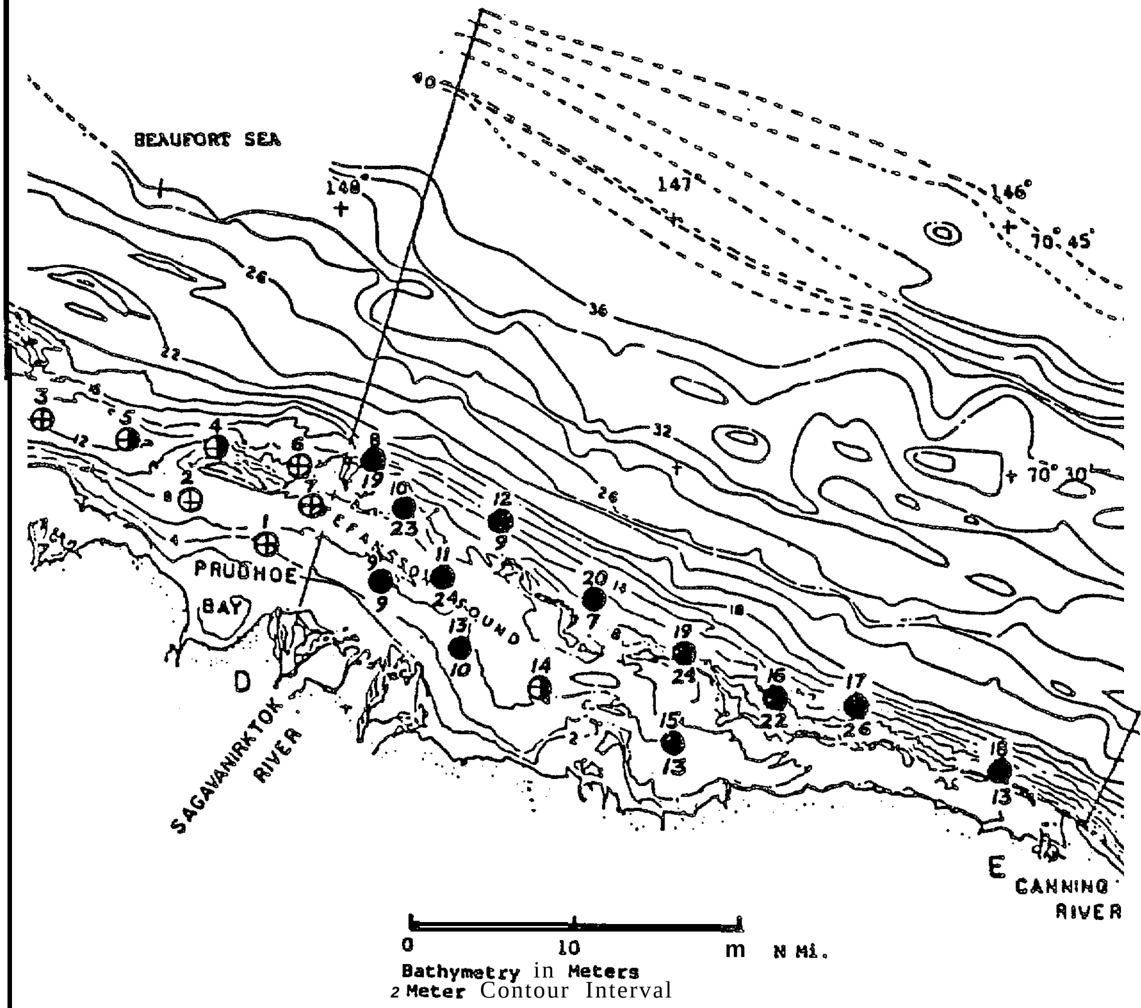
Figure 3.1-32. Summary of available offshore geotechnical information.



Interpreted by Hardy Associates (1978) Ltd. from extensive shallow sea-bottom sampling reported by Barnes and Hopkins (1978). Data to the West of Point Barrow is from Creager and McManus (1967).

rise to a stiffer fine-grained soil cover, is thought to be due to a past history of freezing and thawing. The results from this source are described in many references, including Chamberlain et al. (1978), Sellmann and Chamberlain (1979).

The third source of published geotechnical data is a program carried out under contract for the U.S. Geological Survey, and described by Miller and Bruggers (1980), and Sellmann (1980). Twenty holes were completed to a depth of 24 to 90 m (79 to 295 ft) below seabed, in a much larger area stretching from Long Island to Flaxman Island, and up to 20 km (12 mi) offshore. The boreholes delineated a maximum of about 12 m (40 ft) of softer fine-grained sediments (Holocene age), and concluded that gravel appeared to be shallowest close to the west side of Prudhoe Bay. Ice-bonded permafrost was encountered throughout the area, with somewhat variable ice contents giving rise to an average of about 6 percent strain on thawing. The depth to the top of ice-bonded permafrost is shown on the permafrost map of Figure 3.1-33, which is reviewed more fully later. The clays in the area vary from normally consolidated (i.e., soft) to heavily overconsolidated (i.e., very stiff), depending on the water depth and their geological origin. Overconsolidation in the surface (Holocene) clays may be due to interaction with ice keels, which will give rise to extremely variable properties from place to place. Overconsolidation in the older (Pleistocene) silts and clays is thought to be a product of their history of freeze-thaw and submergence. All of the borehole locations described above are shown on the permafrost map,



HOLES DRILLED DURING 1979 USGS (CONSERVATION DIVISION) SUBSEA PERMAFROST STUDY. HARDING & LAWSON ASSOCIATES DRILL HOLE NUMBERS ARE ABOVE THE DOTS; VALUES BELOW INDICATE DEPTH IN METERS TO BONDED PERMAFROST THAT CONTAINED VISIBLE ICE. HALF-FILLED CIRCLES INDICATE LOCATIONS WHERE BONDED SEDIMENT WAS TENTATIVELY IDENTIFIED. (AFTER HARDING & LAWSON ASSOCIATES, 1979)

Source: Hartz and Hopkins, 1979

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Figure 3.1-33. Holes drilled during 1979 USGS subsea permafrost study.

Figure 3.1-33.

Several other geotechnical programs involving sampling, core retrieval and testing are known to have been carried out by the private sector and are not readily available for this study. The published geotechnical data base is therefore limited to a 100 by 20 km (60 by 12 mi) strip of the study area, mostly to the east of Prudhoe Bay, and is therefore very sparse indeed. However, the earlier bottom sampling results have been generally confirmed by the more detailed drilling that was carried out later, and some general ideas on stratigraphy, geological processes, and the geothermal conditions are available for the study area. Any project involving borrow extraction, site preparation, construction and operation of an offshore structure would certainly require an extensive, site-specific, detailed geotechnical program to drill, sample, in-situ test and thermally instrument the subsoils for the proposed site. It is recognized that the moving pack ice may make an extensive soil investigation program difficult in both summer and winter, but every attempt should be made to obtain the maximum amount of information.

### a) Distribution of Soil Types

The geotechnical map given on Figure 3.1-32 presents the interpreted distribution of bottom sediments from the above referenced material. A description of the character of the bottom sediments, and their geological origin is contained in Section 3.1.8

"Geology and Geologic Hazards." The following is abstracted from Sellmann (1980) and summarizes some of the important conclusions from the USGS drilling programs.

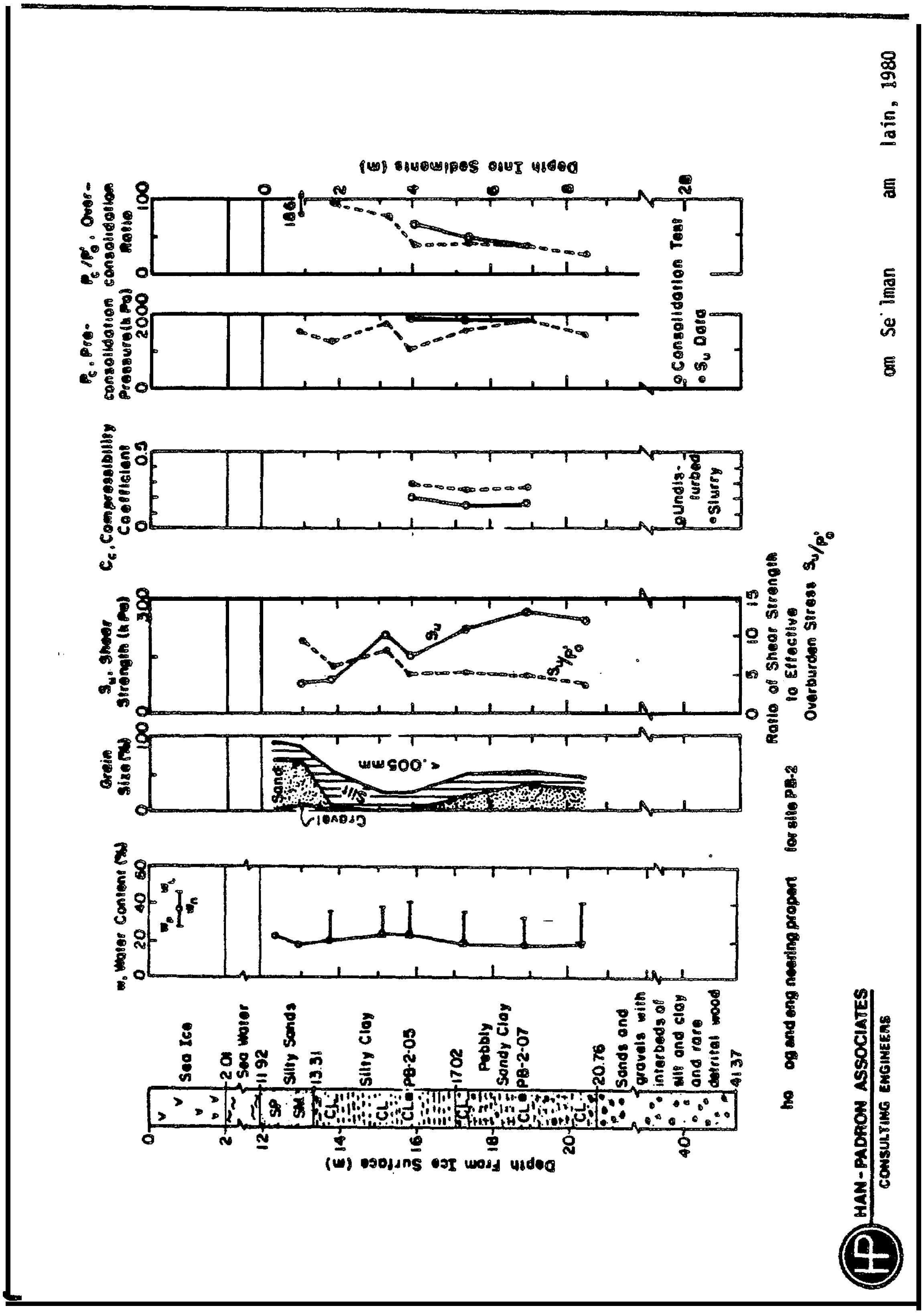
1) The drilling program sponsored by the Conservation Division of the USGS in 1979 provided a considerable amount of new data on the distribution of sediments in the currently proposed lease area on the Beaufort Sea Shelf.

2) The logs for these holes indicate that past data from the Prudhoe Bay area obtained by Osterkamp and Harrison (1976) and Chamberlain et al. (1978) create an anomalous impression of the thickness of the fine-grained section that covers the older Pleistocene sediment which is richer in sand and gravel. The recent USGS study suggests that the thick fine-grained section observed off Reindeer Island (Sellmann and Chamberlain, 1979) may be more representative of the region. Fine-grained sections thicker than 25 m (80 ft) were frequently observed in the offshore holes east of Prudhoe, with the most easterly hole (No. 18) consisting predominantly of fine-grained material over its 92 m (300 ft) depth. The more nearshore holes contained a slightly thinner fine-grained surface section, although more than 10 m (33 ft) of fine-

grained material was common. Determining the properties of this fine -grained unit is further complicated by the fact that portions of many of the sections are ice-bonded and commonly consist of dense, overconsolidated materials.

3) The thickness of this fine-grained material and its properties will have a significant effect on gaining access to the coarser-grained sediment, used for island construction, by penetration of the fine-grained surface section. The variation in thickness and properties of this surface layer will make detailed local site selection for offshore borrow material a necessity.

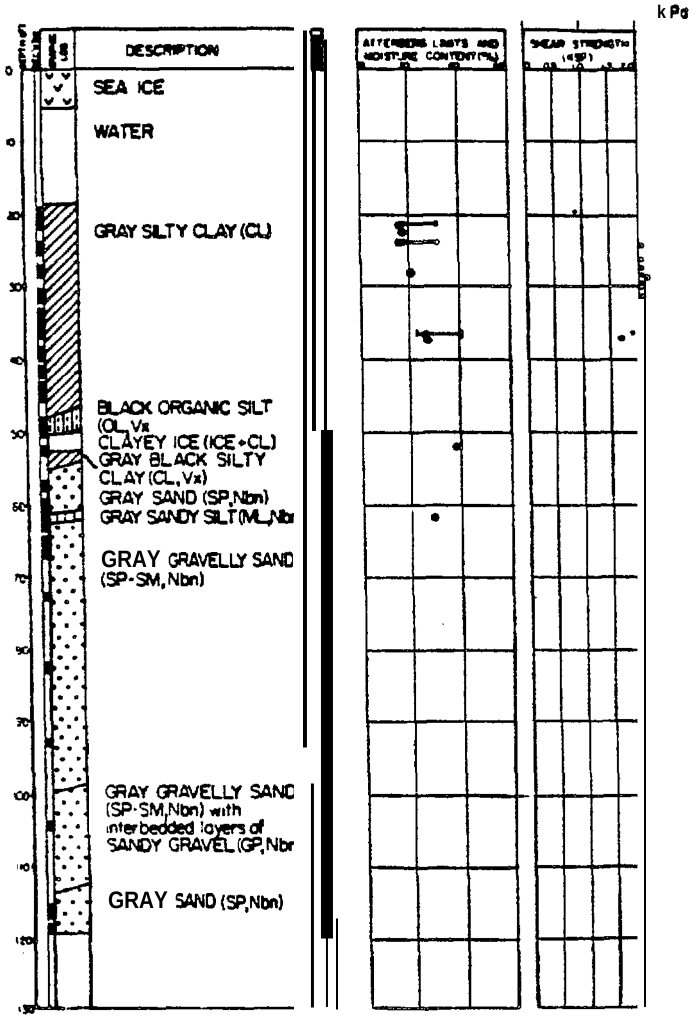
For the purpose of providing typical or illustrative borehole data in areas underlain by different soil types, two boreholes complete with associated engineering data are presented on Figures 3.1-34 and 3.1-35. The borehole indicated on Figure 3.1-34 shows a layer of fine sand with a layer of silt-clay overlying sands (i.e., hole BP-2 in the Prudhoe Bay area), and the borehole indicated on Figure 3.1-35 shows a thick deposit of overconsolidated clay overlying coarse sand (i.e., USGS-HLA hole 13). These borehole logs can be used as illustrative examples when considering various dredging and borrow-removal operations and for considering different possibilities for offshore structure foundations.



ho og and eng neering propert for site PB-2

am Se lman am lain, 1980

**Figure** 3.1-34. Illustrative borehole log for sand bottom sediment conditions.



Log of HLA/USGS boring 13

Adapted f ran: Mi 11 er and Bruggers, 1980

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Figure 3.1-35. Illustrative **borehole** log for clay bottom sediment condition.

### b) Strength and Consistency

The strength and consistency of the near surface soils affect the dredging operation for accessing borrow in a very significant way, and also have a very profound effect on the type and size of structure selected to resist operational and environmental loadings.

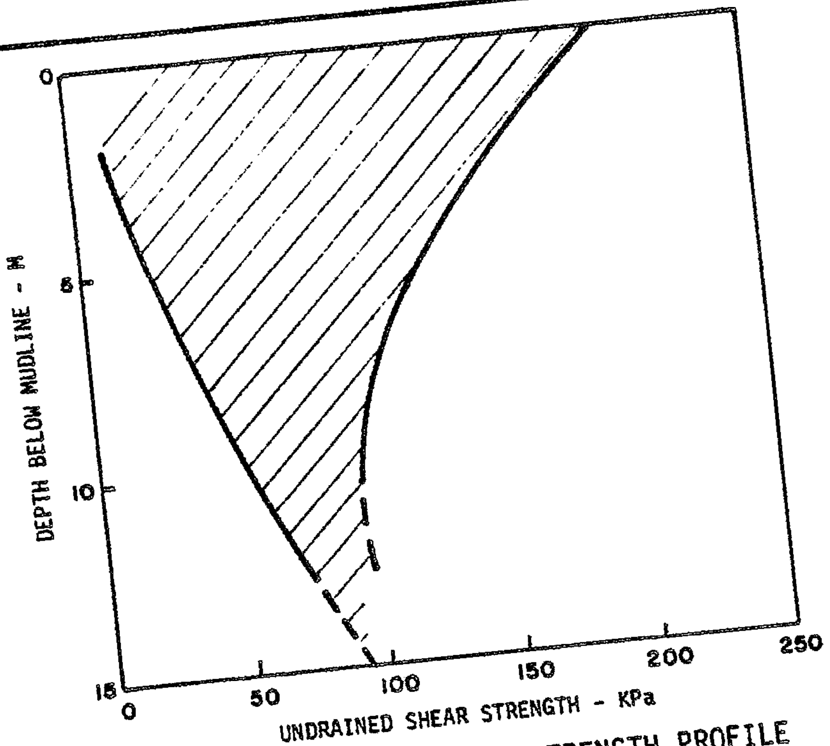
Freezing and thawing, together with other geological agents have caused a variable degree of overconsolidation in the finer-grained silts and clays in the study area. This gives rise to in-situ undrained strengths that may be quite high (80 to 200 kPa or 1,600 to 4,000 psf) near the surface, and may decrease for some depth before increasing again. Overconsolidation ratio is defined as the ratio of the maximum effective stress experienced in the past t-o the present day stress level. This may vary from 2 to 12 in the top 3 m (10 ft) to a range of 1 to 2 at a depth of 21 m (69 ft) (Wang et al., 1982). Undrained shear strength (the shearing resistance of the seabed soils without the benefit of-any improvement from consolidation by the application of surcharge pressures) appears to *vary* generally from about 25 kPa to 200 kPa in the silts and clays.

Shear strength profiles reported by Miller and Bruggers (1980) appear quite constant with depth, with occasional highly plastic or organic silt and clay layers exhibiting lower shear strengths than the range outlined below.

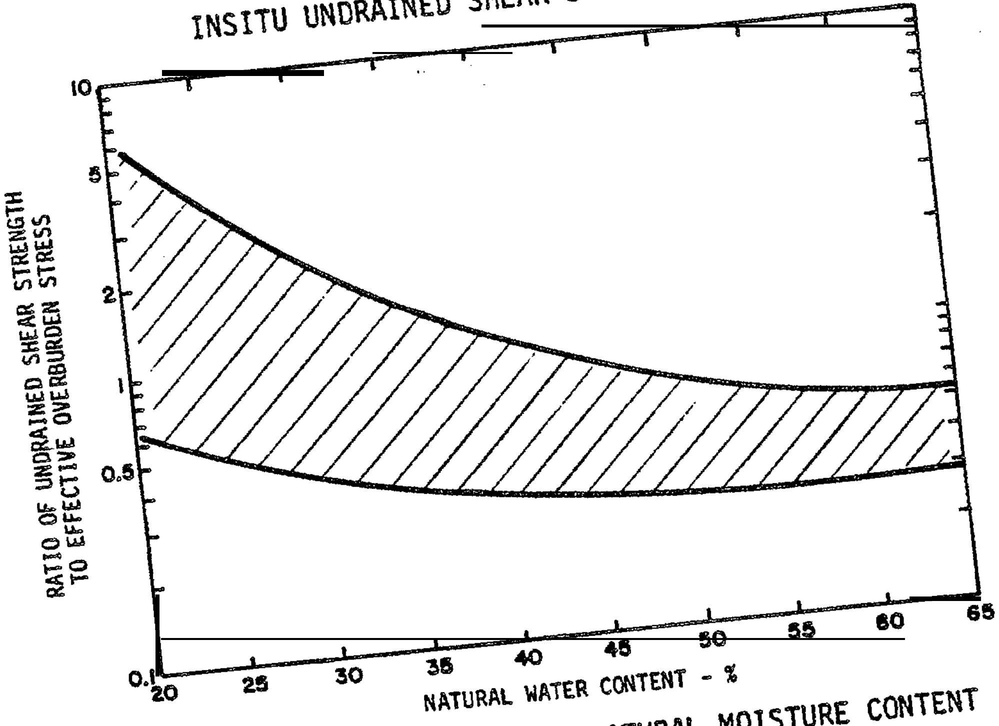
Undrained shear strength is often related to the effective overburden pressure by the ratio of the two parameters, i.e., $c_u/p_0*$ This ratio generally varies from about 0.3 for normally consolidated (softer) silts and clays, to in excess of 3 for stiffer materials of lower water content, as shown on Figure 3.1-36. This ratio tends to correlate reasonably well with the natural water content for the silts and clayey silts of the study area, and appears to have a minimum value of 0.3 for the softer, recently deposited fine-grained soils in the area (Wang et al., 1982),

Strength data for the soil profiles closer to Prudhoe Bay examined by Sellmann and Chamberlain (1980) and others, also provide information on the sand strata, as well as the fine-grained layers. Undrained shear strengths in the silt layers were generally in the range of 50 to 150 kPa (1,000 to 3,000 psf). Higher moisture content clays had strengths in the range of 25 kPa (500 psf). Some information appears to be available on the in-situ density of the sand layers, and may be inferred from Blouin et al. (1971) and Chamberlain et al . (1978). In-situ shear strengths interpreted from static cone tests vary again between 50 to 200 kPa (1,000 to 4,000 psf) for inorganic soils in the Prudhoe Bay area.

Some data on drained strength properties for Beaufort Sea silts are reported by Wang et al. (1982). The effective friction angle of fully drained silts and clayey silts appears to vary between about



INSITU UNDRAINED SHEAR STRENGTH PROFILE



RANGE OF $C_u/P'$ RATIO VS. NATURAL MOISTURE CONTENT

Source: Wang et al., 1982

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Figure 3.1-36. Illustrative data on shear strength of Alaskan Beaufort Sea silts.

32° to over 40°, depending on the soil type and/or natural water content.

For illustrative purposes, engineering properties of two hypothetical seabed soils have been defined: a base case soil and a sensitivity case soil. The base case soil is a silt with a submerged unit weight of 927 kg/ins (58 pcf) and an "undrained" shear strength represented by $c_u/P_o = 0.4$. The sensitivity case soil is a fine sand with a submerged unit weight of 1,040 kg/m$^3$ (65 pcf) and a friction angle of 35°. It must be emphasized that geotechnical conditions are extremely site specific and the selected soil conditions are for the purpose of developing illustrative preliminary cost estimates only.

### c) Consolidation and Stress History

Some data are available from the above-referenced sources on the compressibility of the silts and clays within one part of the study area. Miller and Bruggers (1980) and Sellmann and Chamberlain (1980) report results for the two major investigations carried out. The total settlement, S, of a unit thickness, H, of fine-grained normally consolidated soil beneath a structure that imposes an effective stress of $P_f - P_o$ in the layer is:

$$S/H = [C_c/(1 + e_o)] \log_{10} (P_f/P_o)$$

where: Cc = compression index,

$e_0$ = initial void ratio,

$P_0$ = is the initial effective stress in the soil, and

$P_f$ = is the final effective stress in the soil after time dependent consolidation is completed under the stress increase $(P_f - P_0)$.

The compression index, $C_c$, has been quoted by Miller and Bruggers (1980) as ranging from 0.2 to 0.35 for the soft, upper Holocene sediments, down to 0.05 to 0.15 for the older, deeper sediments. Sellmann and Chamberlain (1980) confirm this general range of 0.1 to about 0.3 for the more compressible clay soils in their review of boreholes near Prudhoe Bay.

When estimating the total settlement in a fine-grained overconsolidated soil, the following equation should be used:

$$S/H = [C_r/(1 + e_0)] \log_{10} (P_p/P_0) + [C_c/(1 + e_0)] \log_{10} (P_f/P_p)$$

where: $C_r$ = recompression index,

$P_p$ = maximum past effective stress in the soil.

The above relationships for settlement allow estimates of total (eventual) settlement to be made for an offshore gravity structure. However, there appears to be little or no information published on the rates of consolidation that might be expected and how long it might take to achieve this total settlement. The rate of consolidation in a soil layer is embodied in the coefficient of consolidation, $C_v$, and standard engineering methods are available to predict the time rate of settlement and dissipation of excess pore pressures in the soil once the general stratigraphy and the parameter $C_v$ are known. If, for example, the soil is sufficiently free-draining so that excess pore pressure will dissipate more or less concurrently with fill placement or ballasting of caisson-type structures, then little concern exists for short term instability or lack of horizontal sliding resistance due to impeded drainage in the seabed soils. In finer-grained clayey silts and clays, rates of consolidation may be very slow, and the designer may have to rely on little more than the initial undrained strength profile for foundation stability and horizontal sliding resistance. Therefore, the coefficient of consolidation is a parameter of primary concern, and unfortunately very little published data are available for samples from the study area.

### d) Thaw Settlement and Frost Heave

If permafrost layers are present within the upper strata of a proposed location, thawing may result from some construction operations, and the operation of warm exploratory or production well casings. Consolidation tests carried out by Miller and Bruggers (1980) below depths of 60 m (200 ft) showed an apparent initial degree of consolidation considerably less than the present consolidation pressures. This indicates that they were likely frozen when sampled and indicates the important fact that frozen, ice-bonded sediments will tend to consolidate when thawed. Limited thaw strain data from the above reference provides a range of' 1 to 16 percent, with an average of 6 percent strain on thaw of ice-bearing sediments.

Frost heave of seabed soils may be encountered where either:

- a fill structure or causeway is constructed in less than about 15 m (50 ft) of water, and permafrost aggregation occurs due to the exposure of the pad surface to the environment, or
- artificial freezing is induced in some form to stabilize softer seabed soils.

Previous experience with projects of this nature (Padron et al., 1984) and observations of naturally occurring ice contents in the Alaskan Beaufort Sea permafrost indicate that the amount of frost heave could be in the range of 2 to 10 percent of the height of soil frozen, depending very strongly on the effective stress level imposed by the structure, the soil type and soil salinity. Generally, there will be little concern for heave in sand or gravel soil types, and techniques are available to bring about marked reductions in frost heave in fine-grained soils (Nixon, 1982; Chamberlain, 1983).

Frost heave will rarely pose serious problems for offshore production structures, but an assessment of its possible magnitude is certainly required to ensure that frost effects are accounted for in the design of offshore structures. However, in some instances, offshore pipelines may be designed to induce freezing as a partial resistance to erosion and ice scour in the overlying soils, and frost heave and its interaction with the structural performance of' the pipeline may become a major issue.

### e) Salinity and Freezing Point Depression

Freezing point depression, and the amount of unfrozen water present at colder temperatures are important design considerations when calculating rates of freezing and thawing, and assessing the strength of frozen fill or seabed materials.

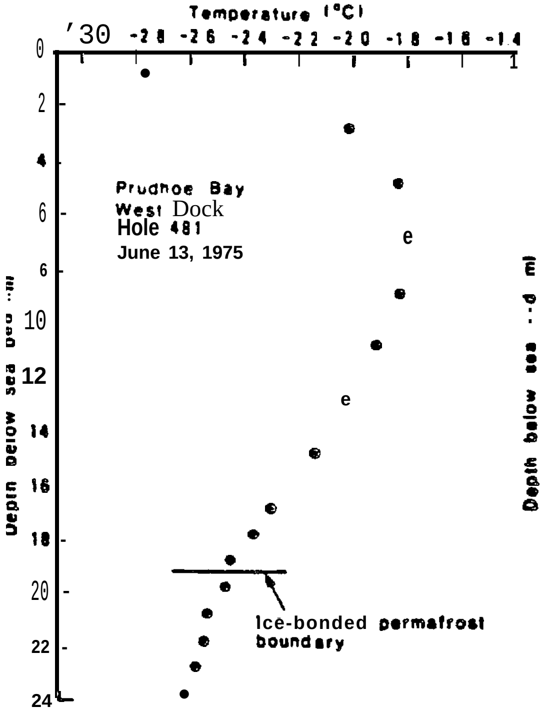
Salinity and freezing point depression (FPD) tests have been carried out on some samples obtained by Miller and Bruggers (1980), and Osterkamp and Harrison (1972). For the offshore Prudhoe Bay area, the sediment freezing temperature is in the range of -1.8°C to -2.4°C. The FPD occurs because of the presence of salts in the pore water of the soils, and freezing temperatures in this range are indicative of pore water salinities equal to or greater than that of normal seawater.

For the wider area covered by Miller and Bruggers (1980), salinities measured in unfrozen samples had freezing point depression values of -0.8° C to -2.8°C, with an average of -1.8°C. This corresponds reasonably well with previous geochemistry studies in the area, and also agrees with the usual value for FPD cited for normal seawater at 30 ppt salinity. The average freezing point depression for frozen samples tested was between -0.6°C to -3.1°C, with an average of -1.5°C.

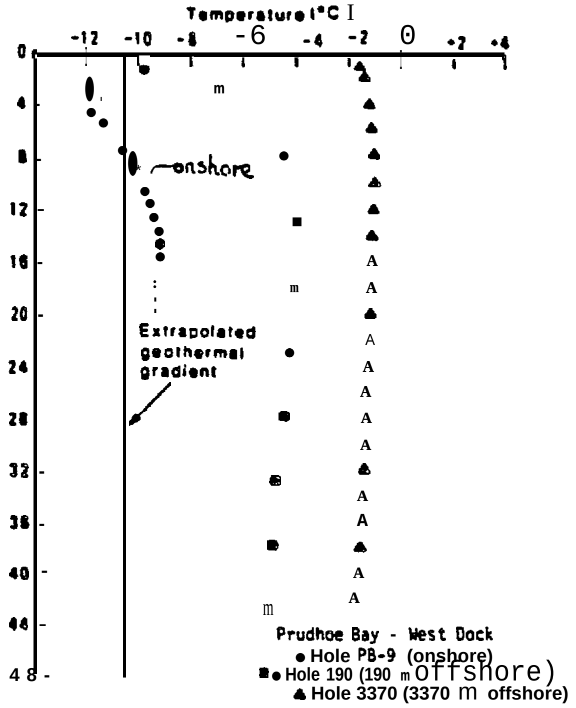
Mean seabed temperatures and subsoil temperature profiles can vary somewhat, depending on disturbance offshore and the rate of coastal erosion or retreat. Where the coastline is reasonably stable, mean seabed temperatures vary from about -1.0°C to -1.5°C for the first 20 km (12 mi) offshore. A summary of data on seabed and subsoil temperatures provided by Osterkamp and Harrison (1982) and by Sellmann and Chamberlain (1980) is given on Figure 3.1-37. When these data are paired with measured values of freezing point depressing it is possible to estimate the presence of ice-bonded permafrost, and some unfrozen water content properties of the permafrost. at sub-freezing temperatures.

### f) Offshore Permafrost

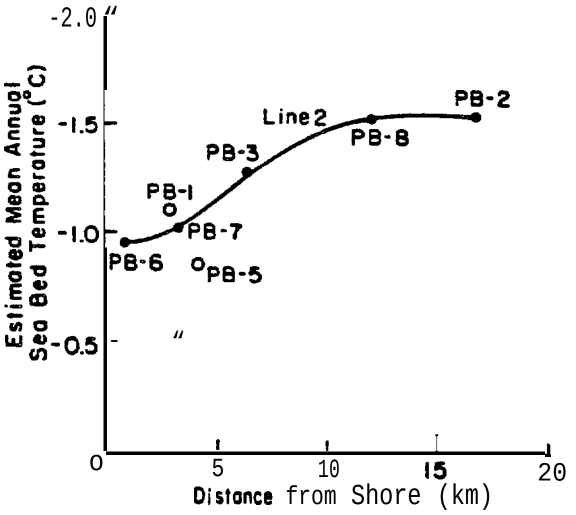
Offshore permafrost can impact very significantly on the feasibility of offshore structures. If present close to the seabed, it may severely hinder borrow or pipeline trenching operations, and allow the possibility of instability if thaw occurs. On the other



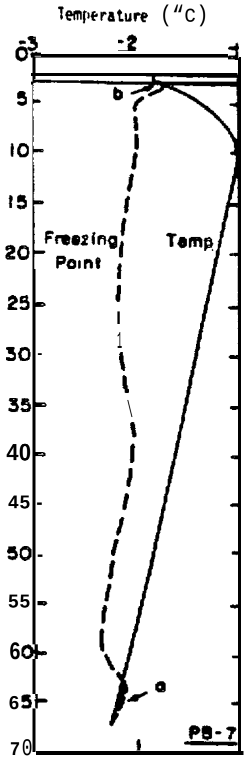
Temperature profile in coarse-grained subsea permafrost sediments at Prudhoe Bay near the west dock. The permafrost is thawed above the break in the temperature gradient at 19.3 m and is ice-bonded below it.



Temperature profiles measured in a line of holes at Prudhoe Bay near the west dock where the shore-line erosion rate is on the order of 1 m/a. These profiles illustrate the response of the permafrost to the warm seabed temperatures.



Mean annual seabed temperatures estimated from drill hole temperature profiles



Comparison of the calculated freezing point and temperature profiles

Source: Osterkamp and Harrison, 1982
Sellman and Chamberlain, 1980

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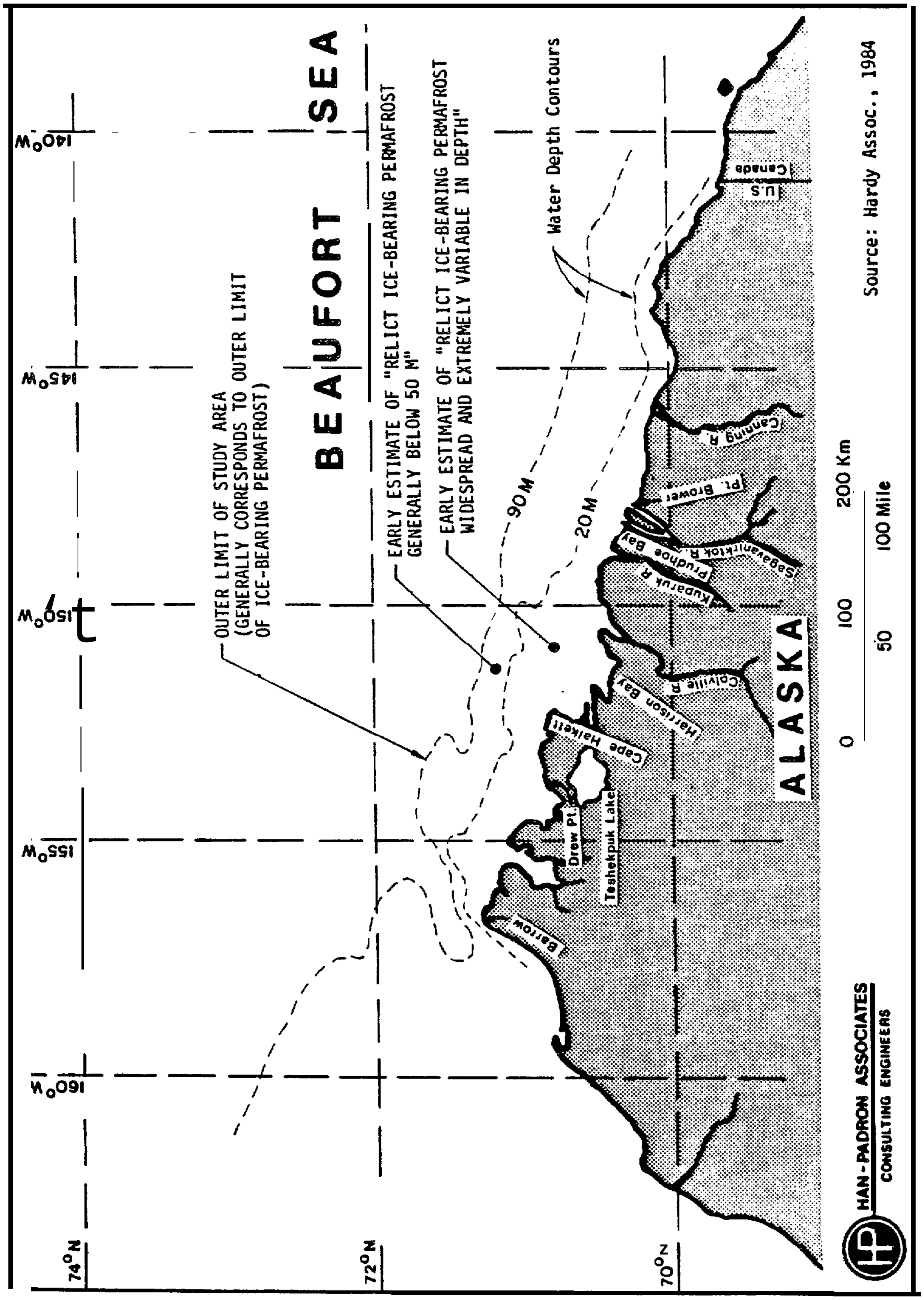
Figure 3.1-37. Examples of seabed temperature and permafrost temperature profiles.

hand, it may prove beneficial when coupled with artificial or natural freezing in enhancing foundation stability and the horizontal sliding resistance of structures to large ice forces (Padron et al., 1984).

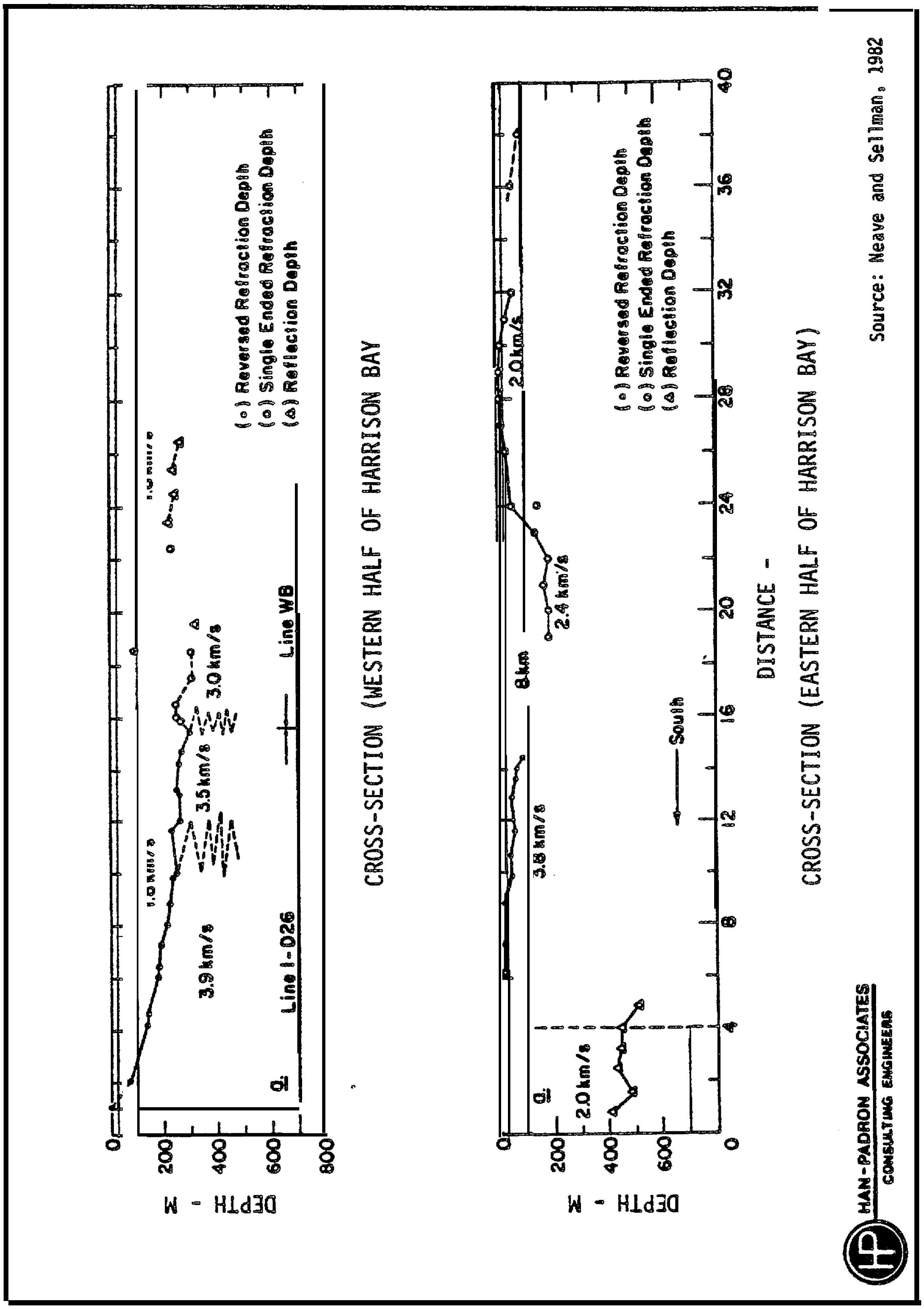
Offshore permafrost has been sampled by drilling and inferred from geophysical observations at many locations in the study area. Neave and Sellmann (1982) provide an interpretation of seismic data, and suggest that ice-bonded permafrost is widespread in the Harrison Bay area. The depth to the top of ice-bonded permafrost falls off rapidly with distance from shore, however, possibly varying from 100 to 300 m (330 to 1,000 ft) at a distance of 20 km (12 miles) from shore. Ehrenbard et al. (1983) provide similar results based on electromagnetic soundings, with a total permafrost thickness of 400 to 500 m (1,300 to 1,600 ft), and the depth to the top of ice-bonded permafrost increasing to about 250 m (820 ft) below seabed at a distance of 9 km (5.6 mi) offshore. Some of the above information is summarized on Figures 3.1-38 and 3.1-39.

In the Prudhoe Bay area, Sellmann and Chamberlain (1980), provide their interpretation of geophysical and borehole data to obtain the depth to ice-bonded permafrost. This depth approaches as much as 140 m (460 ft) about 9 km (5.6 mi) offshore, but the ice-bonded permafrost surface rises to the surface again adjacent to a natural island. These observations, coupled with (a) the published drill hole information, (b) Canadian offshore permafrost experience, (c) older offshore permafrost studies, and (d) known information on



Source: Hardy Assoc., 1984

Figure 3.1-38. Offshore permafrost limits.



Source: Neave and Sellman, 1982

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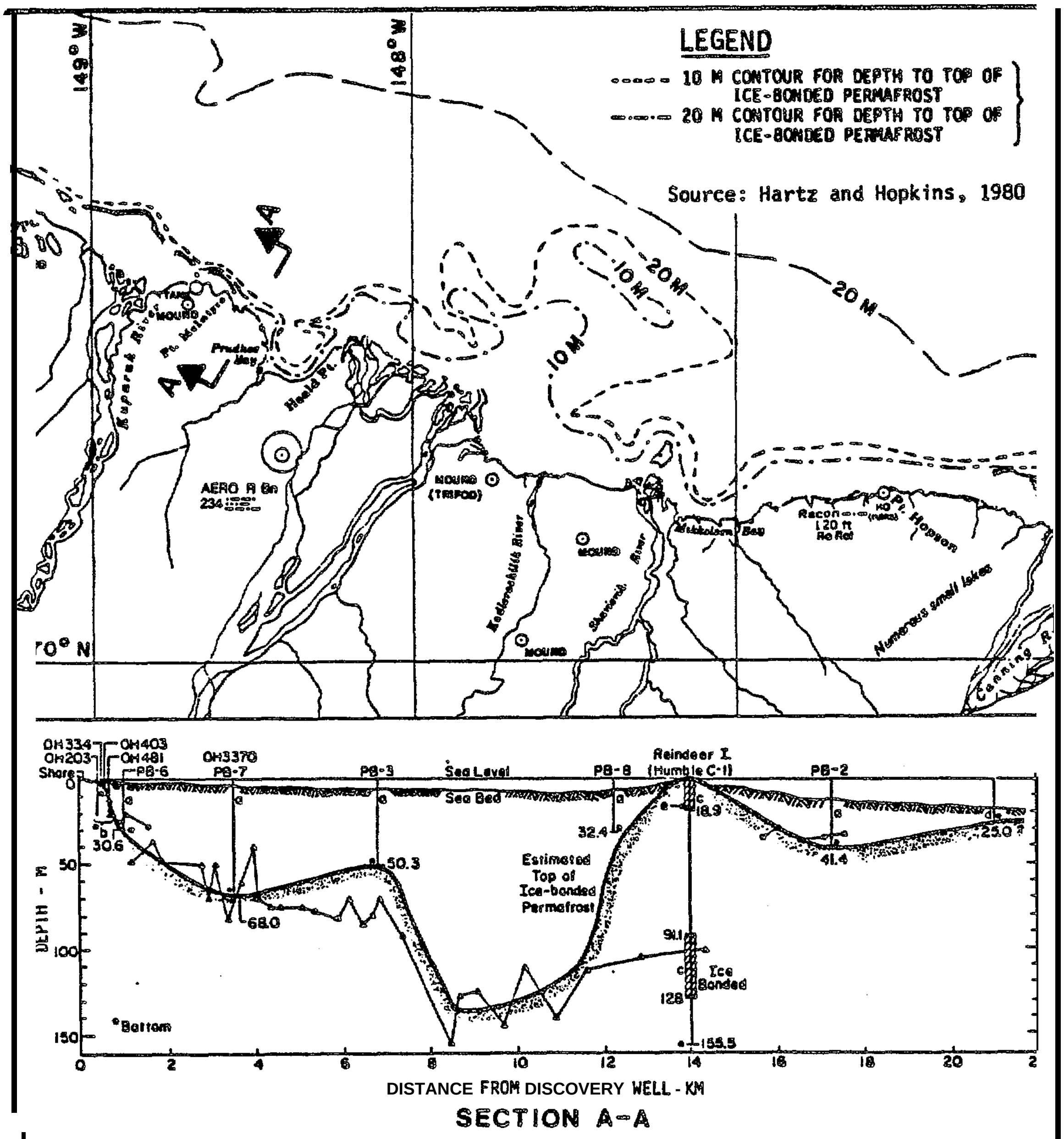
Figure 3.1-39. Harrison Bay permafrost cross-sections.

bathymetry and erosion in the area, have given rise to two maps in the literature. One is an early estimate of offshore permafrost by OCSEAP (1978), and referenced by Sellmann (1980). This is shown with other available permafrost information on Figure 3.1-40. Permafrost is apparently thought to be absent beyond the continental shelf, which also happens to form the boundary for the present study area. Within the study area, two zones are thought to exist. One is underlain by relatively widespread permafrost present at variable depths, and the other is classified as ice-bonded permafrost generally only present below 50 m (160 ft).

The second, more recent estimate of the depth to ice-bonded permafrost in the central part of the Beaufort Sea shelf is presented by Hartz and Hopkins (1980). The 10 and 20 m (33 and 66 ft) contours are shown on Figure 3.1-40

It is apparent, however, that information on permafrost distribution is particularly sparse and unreliable at both the east and west extremities of the study area. It remains a high priority for future geophysical and geotechnical programs to better delineate permafrost distribution in these areas. Even in an area such as Harrison Bay, where considerable geophysical studies have been carried out, little, if any, deep coring has been carried out to determine or prove out the depth to ice-bonded permafrost.



- ● **Refraction** data **(Rogers and Morack 1978)**
- A **Reflection** data **(Rogers and Morack 1978)**
- ■ **Refraction** data **(Rogers, in Barnes and Hopkins 1978)**
- • **Drilling,** sampling. **temperature and chemistry** data **(CRREL-USGS)**
- b **Drilling, sampling, temperature and chemistry data (Osterkamp** and **Harrison 1976)**
- e **Drilling and sampling (Humble C-1, unpublished)**
- d **Drilling (Osterkamp and Harrison 1978a)**
- e **Drilling and temperature data (Osterkamp** and **Harrison 1978b)**

SUMMARY OF AVAILABLE DATA ON DEPTH OF ICE-BONDED PERMAFROST ALONG A LINE FROM THE WEST DOCK AT PRUDHOE BAY THROUGH REINDEER ISLAND. THE DARK SHADED LINE IS THE ESTIMATED POSITION OF THE TOP OF ICE-BONDED PERMAFROST.

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Source: Sellman and Chamberlain, 1979

Figure 3.140. Ice-bonded permafrost in Prudhoe Bay area.

g) Onshore Permafrost

The onshore coastal region in Arctic Alaska is characterized by cold mean annual temperatures and short thaw seasons. Consequently, due to mean annual ground temperatures in the range of -8*C to -10"C, and shallow seasonal active (thaw) layers, borrow operations are usually carried out by ripping or blasting granular borrow in the frozen condition, with transportation and placement also carried out under frozen conditions. This may give rise to settlement and increase in density in the fill material following placement and thaw. The same sands and gravels of Pleistocene age are present along the Arctic coastal area, but are covered by variable thicknesses of fine-grained and icy permafrost. The total thickness of permafrost onshore is approximately 550 m (1,800 ft).

A brief review of borrow sources and onshore permafrost as it affects borrow operations is given in Section 3.4, "Sand and Gravel Resources."

### 3.1.8 Geology and Geologic Hazards

Few geology and geologic hazard data sources pertinent to the Alaskan Beaufort offshore were available prior to the early 1970's. The results of early studies, concerned primarily with bottom sediments and sea ice, were reported in the proceedings of a symposium on "Beaufort Sea Coast and Shelf Research" (Reed and Sater, 1974). With this background, studies then commenced on a wide-ranging environmental impact assessment, under the auspices of the Outer Continental Shelf Environmental Assessment Project (OCSEAP). An interim synthesis volume, published in 1978, reviews and summarizes available data on all aspects of the geology of the area (OCSEAP, 1978). In 1980, existing information on the seabed sediments and their characteristics was reviewed and updated (in light of recent geotechnical drilling results) by Sellmann (1980). Most recently, the Committee on Arctic Sea Floor Engineering, National Research Council, addressed engineering considerations, emphasizing the Alaskan Beaufort offshore (National Academy Press, 1982). Additional proprietary information on the subject exists but has not yet been made publicly available.

Reference has also been made to Grantz et al. (1981) and Grantz et al. (1982) and to a large number of other publications, in addition to the primary information sources noted above. These are cited in the text and referenced in Chapter 8.0.

### a) Geological Setting

In outlining the main features of Alaskan Shelf geology, as they relate to offshore development, emphasis is placed on the Quaternary materials that exist close to the seabed. These deposits, occuring to depths of up to 30 m (100 ft) below mudline, are of both Pleistocene and Holocene age. Bedrock geology per se, concerned with the deeper, older and, in some instances, oil and gas prone formations, is not addressed in detail.

## Bathymetry/Seabed Topography

The area of interest comprises the middle and outer portions of the Alaskan Beaufort Shelf, between the 20 m and 90 m (65 and 300 ft) isobaths (bathymetric contours). Some consideration has been given also to the inner shelf, insofar as such production-related facilities as causeways and pipelines to shore will be located within this zone. Most of the shelf occurs at depths of 50 m (165 ft) or less.

The shelf ranges in width from about 40to 75 km (25 to 47 ml). In general, it slopes relatively uniformly to seaward at an average of 0.5 m/km (2.5 ft/mi); however, as noted by Sellmann (1980), submerged ridges also exist locally. Prominent amongst these features are the ridge to the northeast of Pingok Island, and the Reindeer-Cross Island ridge that extends at least to Narwhal Island, and forms a pr-eminent seabed feature east of Prudhoe Bay. On a more local scale, irregular seabed topography, occurring most notably close to shore, may be related to features such as degrading permafrost, “strudel” scours, etc.

## Marine Geology

The regional distribution and characteristics of sediments close to the mudline between Point Barrow and the Alaskan-Canadian border are reasonably well known (Barnes and Reimnitz, 1974; Barnes and Hopkins, 1978: Sellmann, 1980). The surficial geology of the inner shelf east of the Canning River and west of Cape Halkett is less well understood. Creager and McManus (1967) have described the seabed sediments in the area west of Point Barrow. It should be appreciated that the above distribution is based essentially on shallow oceanographic sediment sampling. Site-specific data on subsurface stratigraphy are rare, and primarily from a relatively small area between Prudhoe Bay and the Canning River (Chamberlain et al, 1979; Miller and Bruggers, 1980).

A synthesis of available data is provided on Figure 3.1-32. The sections that follow describe the regional seabed sediment distribution and summarize the limited, more detailed, data on stratigraphic conditions at depth. In both instances, the wide variability in sediment types and characteristics, even over short distances, may be noted. This emphasizes the need to investigate seabed conditions on a site-specific basis prior to offshore development.

### Seabed Sediments

Figure 3.1-32 shows the distribution of shallow seabed sediments, subdivided on the basis of mean grain size into areas where gravel, sand, silt and clay size materials are dominant (after

Reimnitz and Barnes, 1974; Creager and McManus, 1967). There is reasonable agreement with site-specific borehole information, where available, from the central part of the study area (between Prudhoe Bay and the Canning River).

West of Cape Barrow, sand is the dominant seabed sediment on the inner shelf. Silts and clays predominate further offshore and some gravel exists offshore between Point Lay and Icy Cape (Creager and McManus, 1967).

Clays and silts predominate in the area between Cape Barrow and Cape Halkett, and coarser sediments (sands and gravel) are apparently rarely present except in the vicinity of barrier islands and the shoals that lie seaward of the barrier islands and the Weller Bank. This is largely a function of the fact that the sediment brought down by the low energy gradient rivers in this area and eroded from coastal bluffs is dominantly fine-grained (Barnes and Reiss, 1981; Reimnitz and Kempema, 1981; Hopkins and Barnes, 1978; Reimnitz and 'Mauer, 1978).

The distribution of seabed sediments to the east of Cape Halkett is more complex. Silts are dominant on the middle shelf with sands occuring widely on the inner shelf and close to the shelf break (in a relatively high energy environment, where gravels also exist locally). Gravelly sediments are also prevalent on the inner shelf close to the mouths of some of the major rivers. Clays are found close to or seaward of the break in the continental shelf in the eastern part of the area. In general, seabed sediments appear to become coarser towards the east (Figure 3.1-32).

## Subsurface Stratigraphy

Geotechnical drilling in Prudhoe Bay (Chamberlain et al., 1978; Sellmann and Chamberlain, 1979) and between Long Island and Flaxman Island (Miller and Bruggers, 1980) indicates that four main geological units are present in the subsurface, i.e., within 30 m (100 ft ) of the mudline. These are of both Holocene and Pleistocene age and may or may not all be present at a specific site. The genesis of the Beaufort Sea shelf has not been resolved. It is not clear whether the Holocene thickens or thins seaward. Resolving this question is important in designing deep water structures.

The uppermost unit comprises a sequence of Holocene silts, sands and clays, deposited under marine conditions during the approximately 10,000 years since submergence of the shelf. In the Prudhoe Bay area, this unit is generally 5 to 10 m (15 to 30 ft) thick; however, to both the east and west (where data are lacking) the fine grained sediments may be considerably thicker. Greater than 13 m (43 ft) of Holocene material was recorded close to Stockton Island (Miller and Bruggers, 1980).

As noted by Barnes and Hopkins (1978), some areas of the shelf lack any substantial thickness of Holocene sediment. In these areas the underlying Pleistocene Flaxman Formation, consisting of marine sandy to clayey silt, crops out on the sea floor. The silt unit is generally overconsolidated and may be in excess of 7 m (23 ft) thick (Chamberlain, 1978).

Frequently, even where it is overlain by a considerable thickness of Holocene sediment, a deposit of sand and/or gravel exists above the Flaxman Formation. Although ice-rafting and coastal erosion have been suggested as possible sources for this material, it is now considered to be primarily a lag deposit, resulting from erosion of the Flaxman. The sand and gravel lag is 1 to 1.5 m (3 to 5 ft) thick.

The lower-most unit is a sand and gravel deposit of Pleistocene age. Available evidence suggests the distribution of this unit is widespread and it is almost everywhere present (though at very variable depths) between Prudhoe Bay and the Alaskan-Canadian border. It is of considerable interest as a potential source of granular borrow material. The Pleistocene sands and gravels also occur beneath the Arctic Coastal Plain and according to Hopkins (1978), become finer-grained to seaward.

b) Geologic Hazards

Eight geology-related conditions are identified that may potentially have adverse impacts on Alaskan Shelf development:

- Fine-grained soils
- Permafrost
- Natural gas hydrates
- Shallow gas deposits
- Seismicity
- Ice gouging
- "strudel" scour
- Coastal erosion.

The following sections briefly describe the possible geologic hazards and identify their likely impacts relative to offshore development.

## Fine-Grained Soils

Two main fine-grained soil units occur in the Alaskan Shelf: Holocene silts, fine sands and clays, and Pleistocene clayey to sandy silts (Flaxman Formation). Each has very different engineering characteristics, so that, paradoxically, they may both constitute potential geologic hazards while providing good conditions for development.

The recent (Holocene) sediments are soft, loose and normally consolidated (Section 3.1.7), and may be expected to provide poor foundation conditions for offshore structures. Conversely, however, provided they are not too thick (i.e., beyond dredge depth capacity), they are easily removed to provide access to offshore granular borrow deposits, or a better bearing stratum for foundations.

The Flaxman Formation silts, on the other hand, are stiff to hard and frequently overconsolidated {Section 3.1.7). Thus, while potentially providing good foundation conditions for offshore structures, this unit may (if of sufficient thickness) make overburden removal, to reach underlying borrow materials, difficult and, in some situations, impractical.

### Permafrost

Subsea permafrost may constitute a hazard, particularly near to the shoreline, due to the potential for thaw and subsidence and frost heave. Permafrost is addressed in detail in Section 3.1.7.

### Natural Gas Hydrates

Natural gas hydrates are ice-like inclusion compounds in which guest natural gas molecules fit into the structural voids in the lattice of a host water molecule. Their stability is a function of temperature and pressure.

In general, the most favorable conditions for hydrate formation are a low surface and mean ground temperature and low geothermal gradient (Judge, 1982). Under such favorable conditions, gas hydrates may be encountered onshore within the depth range 140 to 1,900 m (460 to 6,200 ft). Offshore the hydrate-prone zone may extend to a depth of 750 m (2,500 ft) beneath 200 to 300 m (650 to 1,000 ft) of water. In continental shelf areas (such as the Beaufort Shelf) hydrates may be expected to exist as a relict (and likely degrading) phenomenon at depths of between 200 and 1,800 m (650 and 5,900 ft).

The distribution of natural gas hydrates in the Prudhoe Bay area has been described by Collett (1983) and Lachenbruch et al. (1982). Neave and Sellmann (1982) have inferred, based on attenuation of seismic data, that shallow gas (which they suggest is related to hydrate decomposition) occurs close to the seabed beneath much of Harrison Bay.

In terms of offshore development, the influence of natural gas hydrates depends on their distribution, depth and stability. On the Beaufort Shelf, hydrate degradation may result in-development of underconsolidated and low strength soil conditions, and pressurized, high gas content sediments. It may also have implications for well completion.

## Shallow Natural Gas Deposits

Concentrations of natural gas located in pockets as shallow as

15 m (50 ft) below the seabed may occur throughout the study area. As noted above, seismic data inidicate that shallow gas occurs beneath much of the Harrison Bay area. The source of these gas deposits is still subject to some speculation. As suggested by Neave and Sellmann (1982), they may result from the decomposition of natural gas hydrates. Other possibilities include seepage from deeper oil/gas reservoirs and decay of organic sediments.

## Seismicity

Most parts of the Alaskan Shelf and adjacent Arctic Coastal Plain are considered to be of low seismicity, on the basis of existing information. The seismicity rating for the entire study area, according to API RP2A, is Zone 1 with G = 0.05. However, a more seismically active zone of Holocene uplift and faulting near Camden Bay and Barter Island is known to exist and the Shelf to the east may also be more active (National Academy Press, 1982).

A summary of available data was provided by Barnes and Hopkins (1978) as follows:

1. The seismic zone around Barter Island and Camden Bay is an integral part of the central Alaskan seismic zone. Earthquakes located in the area are shallow (focal depths range from 0 to 20 km).

2. Between 1968 and 1978, the largest earthquake ($M_L = 5.3$) had an epicenter in an area located 30 km (18 mi) offshore from Barter Island. The main shock was followed by a series of aftershocks, the locations of which show a ENE-WSW seismic trend along the axial traces of offshore folded structures. However, because of the nature of existing instrumental coverage, the magnitude and location of earthquakes in this area are relatively uncertain compared, for example, to California earthquakes.

3. Because of the low activity rate, the available data represent. too short a time interval for the precise determination of recurrence rates for earthquakes of magnitude greater than 5.0.

4. Other earthquakes in northeast Alaska, of magnitude smaller than 5.0, tend to be distributed on the eastern side of the interface between the Colville geosyncline and the Romanzov Mountains. A notable concentration of epicenters occurs on the south side of the Brooks Range. Generally events of this size and this far removed from the region of interest do not generate ground motions of any significant interest in design.

Barnes and Reimnitz (1974) suggest that the above data indicate the need for man-made structures to be designed for ground vibrations from a shallow earthquake of magnitude at least 6.0. Linear structures, like pipelines, should have appropriate design provisions for periodic displacements of small extent at the crossings of seismically active geological structures (such as those noted above).

For preliminary design purposes, the following seismic conditions have been used:

| | |
|---|---|
| API Seismic Zone | 1 |
| API Acceleration Factor | 0.05 |

## Ice Gouging

Gouging of the seabed by the keels of sea-ice pressure ridges and ice island fragments is a common phenomenon on the Alaskan Beaufort Sea Shelf. Surveys reveal the presence of characteristic ice gouge burrows in water depths greater than 100 m (330 ft) on the Alaskan Shelf (Barnes and Reimnitz, 1974), but it is doubtful if gouges in this great a depth occurred in modern times. Figure 3.1-41 schematically illustrates an idealized ice gouge feature and the associated terminology.

Site-specific information on ice scour/gouge distribution and frequency is limited to small areas of the inner and middle shelf, between Cape Halkett and Flaxman Island. Gouge occurrence is apparently controlled by water depth, local bathymetric features,

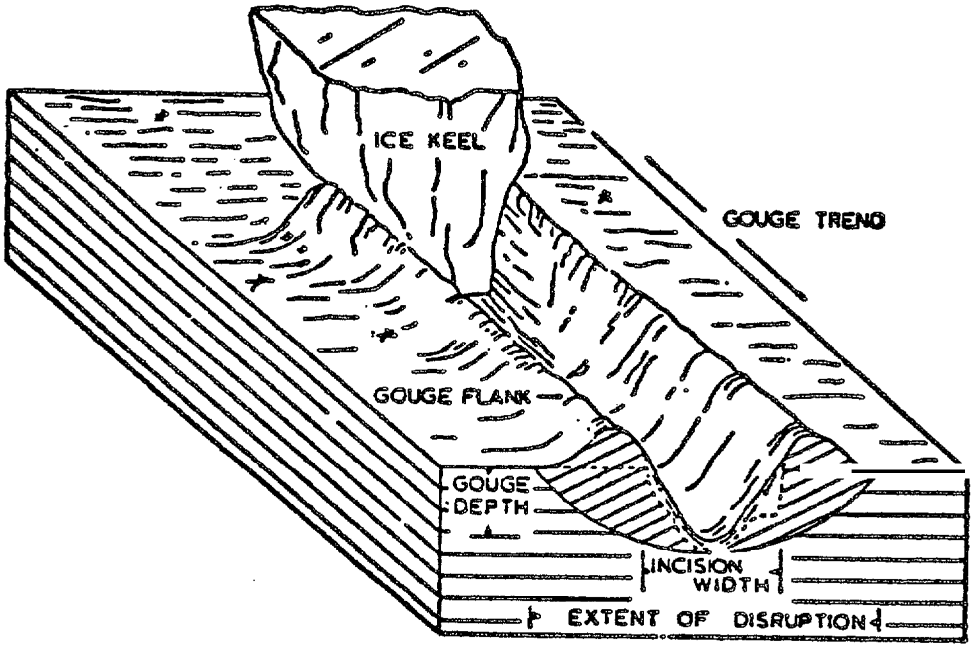

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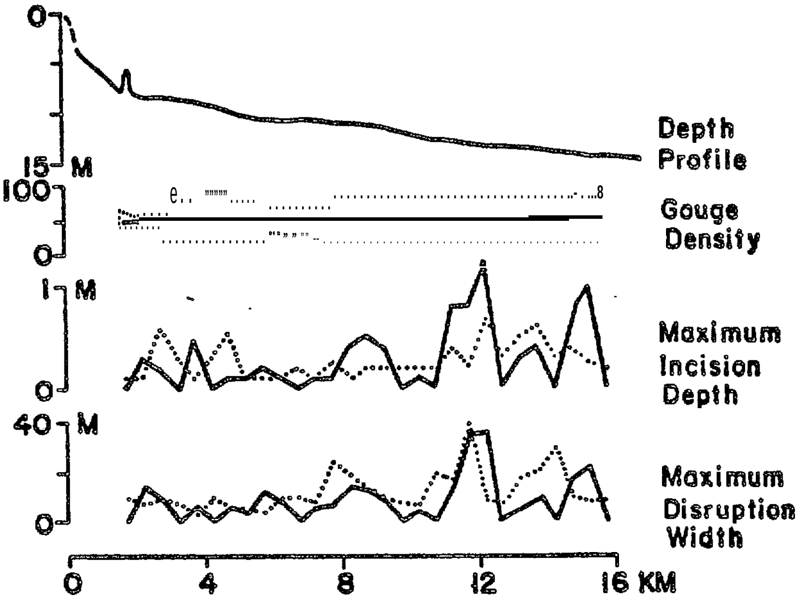
Figure 3.1-41. Schematic illustration of ice gouge.

sediment type and the dynamic movement of sea ice. Occurrences peak in 20 to 30 m (65 to 100 ft) of water beneath the ice shear ("stamukhi") zone, decreasing both shoreward and seaward.

As a generalization, gouges are commonly more than 1 m deep within and seaward of the zone of grounded ice ridges but less than 1 m deep to shoreward of this zone. In the Alaskan Beaufort, the deepest recorded gouge is 5.5 m (18 ft) deep, in 38 m (125 ft) of water. Gouge/scour depths increase with water depth but the features are less frequent in deeper water.

Information on the frequency of gouge recurrence is sparse. Available information shows that gouge frequency can be exceedingly high, to the extent that the seabed may be totally reworked every year, in areas of persistent grounded ice in the shear zone. Gouging is also frequent in shallow waters, such as those of Harrison Bay, where the seabed undergoes complete reworking every 50 years to an average depth of 0.3 m (1 ft). Data on ice gouge characteristics to the northwest of Thetis Island, Harrison Bay, are shown on Figure 3.1-42.

Ice gouges and their dynamic formation mechanism are of considerable significance in relation to offshore development activities. Their distribution, frequency of formation and depth will influence the design of seabed pipelines and well completions, as well as other seabed installations planned on the inner shelf.



ICE GOUGE CHARACTERISTICS ALONG A TRACKLINE NORTHWEST OF THETIS ISLAND IN HARRISON BAY. DATA HAVE BEEN SUMMARIZED FOR 500-M SEGMENTS. THE DOTTED LINES REPRESENT A SUMMARY OF ALL GOUGES OBSERVED ON 1975 DATA WHILE THE SOLID LINES REPRESENT THE CHARACTERISTICS OF NEW GOUGES THAT WERE MADE BETWEEN 1975 AND 1976.

Source: OCSEAP, 1978

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**Figure 3.1-42.** Ice gouge characteristics.

Considerable lateral variability in sediment strength properties can be associated with these features, where rapid infilling of soft sediment occurs in regions of dense clay common to much of the shelf.

The interaction of a bottom founded structure and the seabed will be important in areas where the seabed is heavily gouged. Such structures will be sensitive to the uneven seabed in terms of structural components, foundation resistance, and installation/ removal procedures.

### Scour Pits or "Strudel" Scour Depressions

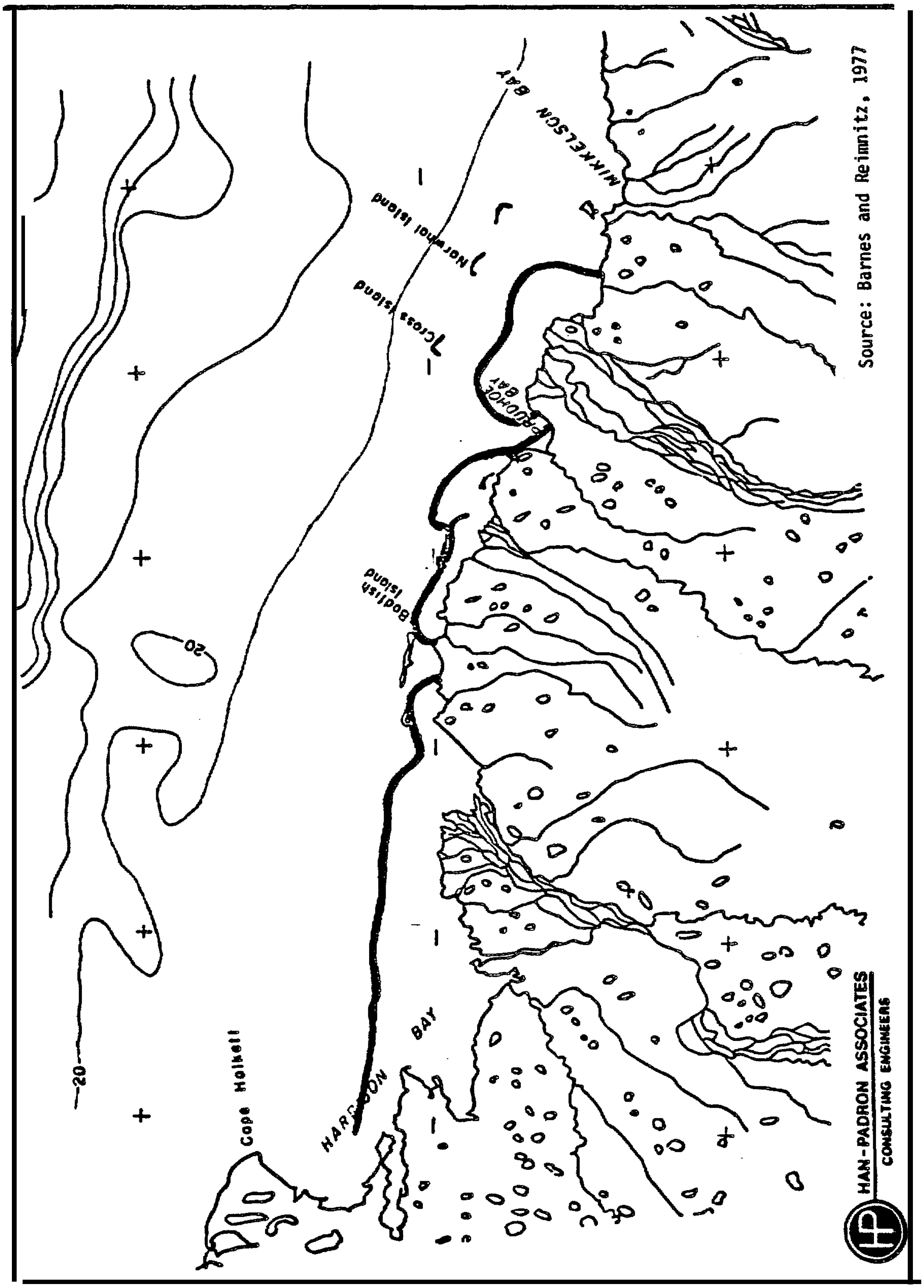
Scour pits or "strudel" scour depressions are a feature that is unique to the inner shelf in Arctic regions. During spring break up, discharge from the major streams on the Arctic Coastal Plain becomes very great, at a time when much of a stream is frozen to its bed. During the period of initial peak flow, river water flows over the sea ice reach depths of 1 to 3 m (3 to 10 ft), and, in some areas, extend many kilometers offshore. The water drains from the sea ice surface through imperfections, such as holes and cracks, in the ice. In these zones of localized drainage, bed scour occurs that can form cylindrical depressions as much as 4 m (13 ft) deep and tens of meters across (Reimnitz et al., 1974). Sediment excavated by this hydraulic mechanism is redeposited on the flanks of the depression, forming debris mounds. An indication of the outer limit of these features as observed between Harrison bay and Prudhoe Bay, is shown on Figure 3.1-43 (Barnes and Reimnitz, 1974).

The occurrence of "strudel" scour depressions is confined almost entirely to the inner shelf (Figure 3.1-43). In terms of offshore development, these features may be significant relative to routing and construction of pipelines (and t-elated facilities such as causeways) by which production may be brought to shore (Reimnitz et al., 1977).

## Coastal Erosion

Thermal erosion, a process unique to permafrost regions, gives rise to dramatic coastal retreat and shore line modifications. Figure 3.1-44 (from Hopkins and Barnes, 1978), provides an indication of coastal erosion and shoreline retreat rates. According to Hopkins and Barnes:

> "Coastal retreat proceeds at the relatively modest average rate of about 1 m per year along the Canadian Beaufort Sea coast between the Mackenzie River Delta and Demarcation Point. Coastal retreat along the mainland coast between Demarcation Point and the Colville River averages about 1.6 m/yr, although local short--term rates may be much higher. Rates of shoreline retreat on the Pleistocene remnants range from 1.5 m/yr on Pingok Island to about 3.5 m/yr on Flaxman Island. The sand and gravel islands are retreating



Source: Barnes and Reimnitz, 1977

Figure **3.1-43.** Outer limit of "strudel" scouring observed between Harrison Bay and **Prudhoe** Bay.

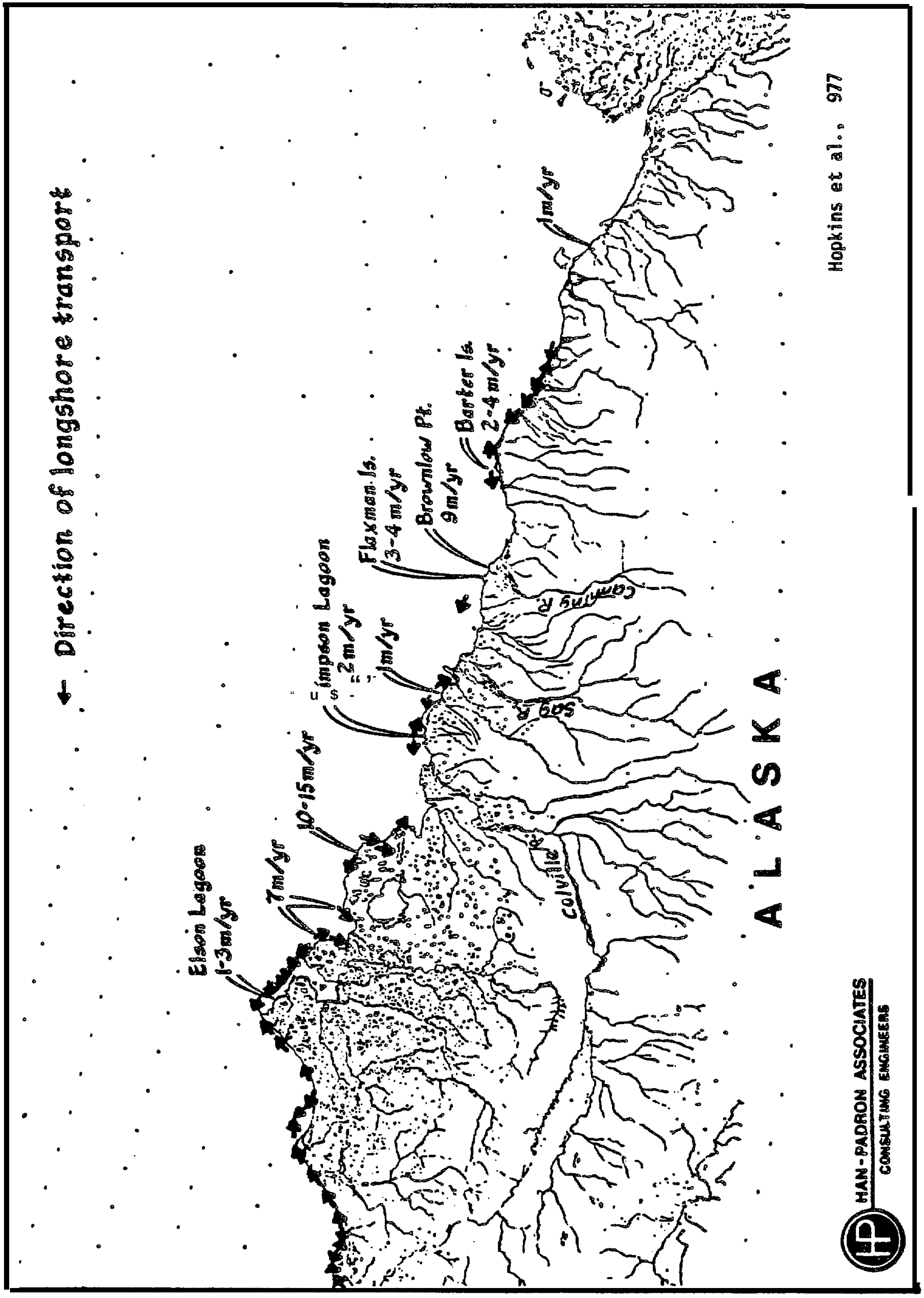


Figure 3.1-44. Long-shore drift and coastal erosion rate.

at slightly higher rates, between 3 and 7 m/yr. Average rates of mainland coastal retreat are highest from Harrison Bay westward to Barrow. An average retreat, rate as high as 4.7 m/yr is suggested for this segment of the coast, and Leffingwell reported short term erosion rates as great as 30 m/yr at Drew Point and Cape Simpson."

Such changes are significant concerns in regard to design, construction and operation of pipelines, causeways and other nearshore facilities associated with Beaufort Sea production.

### 3.1.9 Meteorological Conditions

Climatically, the region is in the Arctic zone, and is thus characterized by relatively cold temperatures, low precipitation and persistent winds. The coast is relatively dry, especially during winter. However, Barter Island, which is near the eastern study area, usually reports 50% more precipitation and snowfall than Barrow, which Is near the western study area. Although rain accounts for most of the annual precipitation, heavy snows typically begin during the month of September, and the ground is generally snow covered from October through June. Mean annual maximum and minimum temperatures and average annual precipitation and snowfall are obtained from the Climatic Atlas (Brewer et al., 1977).

Optimum visibility, in general, has been reported for the months of March, April, June and July. Meanwhile, the poorest visibility has generally been reported for August through December, with fog a major contributor during August and September, and snow a leading contributor from September through December. The annual percent frequency of' occurrence of various precipitation types and visual obstructions is obtained from the Climatic Atlas (Brewer et al., 1977). The precipitation and visual obstructions include rain or drizzle, freezing rain or drizzle, snow or sleet, fog, smoke or haze, and blowing snow. The average of the values recorded at Barrow and Barter Island were used for the study area.

For preliminary analysis, the following meteorological conditions have been assumed:

| | |
|---|---|
| Average annual max. temperature | -10°C (14°F) |
| Average annual min. temperature | -16°C (3°F) |
| Average annual precipitation | 12 cm (5 in.) |
| Average annual snowfall | 73 cm (29 in.) |

Average annual % frequency of occurrence of precipitation types

| | | |
|---|---|---|
| | Rain or Drizzle | 4.4 |
| | Freezing Rain or Drizzle | 0.6 |
| | Snow or Sleet | 19.0 |
| Total | Precipitation | 24.0 |

Average annual % frequency of occurrence of reduced visibility

| | | |
|---|---|---|
| | Fog | 16.7 |
| | Smoke or Haze | 0.1 |
| | Blowing Snow | 10.0 |
| Total | Reduced Visibility | 26.8 |

### 3.1.10 Daylight Duration

Because of the extreme northern location of the study area, daylight is very limited or non-existent during the winter months. Figure 3.1-45 indicates the amount of daylight throughout the year at a latitude of 71°N. The chart is based on a chart in the Climatic Atlas, whose source is the U.S. Naval Observatory (1945). The chart is accurate for the entire twentieth century. It should, however, be noted that the duration of daylight for high latitudes is increasingly dependent upon atmospheric conditions and refraction. Thus some departure from the values depicted in the chart can be expected.

### 3.1.11 Summary of Environmental Design Criteria

A summary of the environmental design criteria used in the preparation of this study is presented in Table 3.1-1.

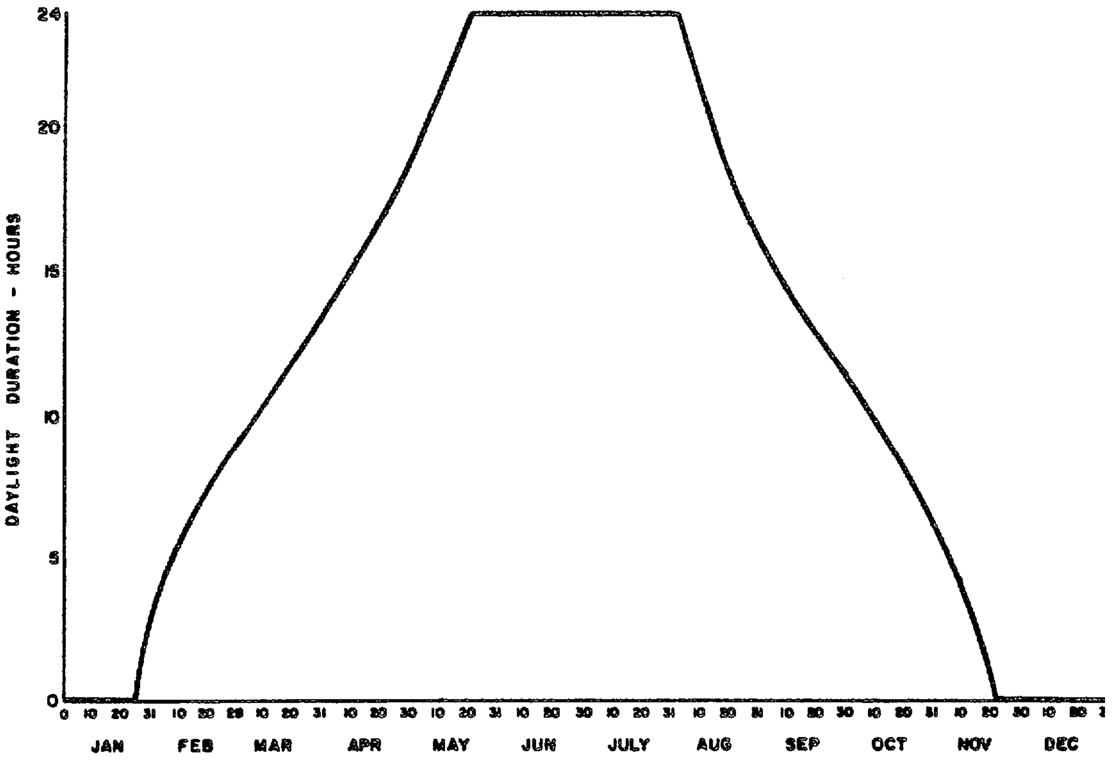


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Figure 3.1-45. Daylight duration at 71°N latitude.

## TABLE 3.1-1

| | | |
|---|---|---|
| **ICE CONDITIONS** | | |
| Ice Strength: | | |
| Annual Ice | | |
| - Compressive | 5,900 kPa | |
| - Flexural | 620 kPa | |
| - Shear | 1,000 kPa | |
| Multi-Year Ice | | |
| - Compressive | 8,300 kPa | |
| - Flexural | 760 kPa | |
| - Shear | 1,400 kPa | |
| Ice Modulus of Elasticity | | |
| Annual Ice | 3,000 mPa | |
| Multi-year Ice | 3,800 mPa | |
| Level Ice Characteristics | Exploration | Production |
| Annual Ice | | |
| - Average Salinity | 6 ppt | 6 ppt |
| - Average Temperature | -10°C | -10°C |
| - Maximum Thickness | 2 m | 2 m |
| Multi-year Ice | | |
| - Average Salinity | 3 ppt | 3 ppt |
| - Average Thickness | -15°C | -15°C |
| - Maximum Thickness | 6 m | 10 m |
| Ice Ridge Consolidated Thickness | Exploration | Production |
| Annual Ice | 2.5 m | 3.5 m |
| Multi-year Ice | 8 m | 12 m |
| Ice Drift Velocity | | |
| Open Water (Summertime) | 1.0 mps | |
| Ice Packed (Wintertime) | 0.15 mps | |
| Ice Coefficient of Friction | | |
| Ice/Steel | 0.15 | |
| Ice/Concrete | 0.30 | |
| **WAVES** | | |
| Maximum Wave Height | 12 m | |
| Corresponding Wave Period | 11 sec | |
| **WINDS** | | |
| Maximum One-Minute Wind | 50 mps | |
| **CURRENTS** | | |
| Maximum Surface Current | 1.0 mps | |
| Maximum Bottom Current | 0.25 mps | |
| **TIDES/STORM SURGE** | | |
| Tidal Range | 0.2 m | |
| Storm Surge | 2.0 m | |
| **GEOTECHNICAL CONDITIONS** | | |
| Soil Type | Silt | |
| Submerged Unit Weight | 927 $kg/m^2$ | |
| "Undrained" Shear Strength | $c_u/P_o = 0.4$ | |

## 3.2 ENVIRONMENTAL FORCES ON OFFSHORE FACILITIES

### 3.2.1 Ice Forces

The most significant environmental forces affecting the design of exploration and production platforms located in the Beaufort Sea are forces resulting from the movement of ice floes. The study region of 20 to 90 m (65 to 300 ft) water depth encompasses both the land fast and transition (Stamukhi) ice zones, including the highly active shear zone (Figure 3.2-1). Because of the varied water depths, geotechnical conditions, ice features, and floe characteristics throughout the study region, a multitude of structural configurations are plausible. Consequently, there is a need to determine ice forces resulting from the various failure modes induced by this range of configurations.

Only bottom founded type exploration and production platforms are considered in the determination of ice forces in this section. The costs of floating exploration platform concepts have been estimated on an ice Class basis. The hulls of these vessels are designed to an ice Class rating usually well above the ice characteristics corresponding to the capacity of the mooring or positioning system. The ice Class hull rating, usually a minimum of Class 4, must satisfy pollution control regulations regarding hull damage. The limiting factor for ice loading on the vessel is the capacity of the mooring system, which is not subject to the loads

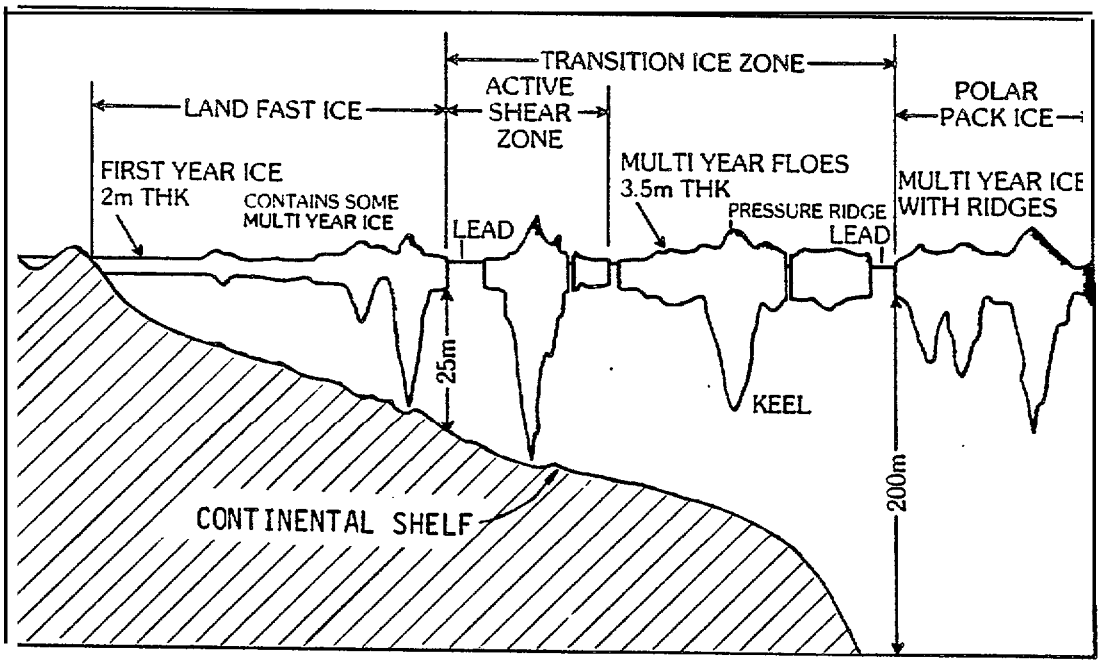

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Figure 3.2-1. Beaufort Sea ice zones.

resulting from the design ice conditions stated in Section 3.1. The maneuverability of these vessels and the relatively minor consequences of anticipated break-away episodes permits the design of the mooring system to be guided only by economic considerations regarding the length of the vessel's operating season.

Existing and proposed bottom founded exploration and production platform concepts range from wide, vertical sided structures (caisson retained island, etc.) (Figure 3.2-2) to narrow, conical shaped profiles (Conical Monopod, ACES, etc. ) (Figure 3.2-3). Ice features of concern in the design of these structures include first year (annual ) level ice and pressure ridges in the slow or non-moving landfast ice zone and annual and multi--year level ice, multi-year pressure ridges, and ice islands in the transition ice zone. In addition, the transition zone provides distinct seasonal differences. During the winter season, ice coverage is thick and compact but relatively slow moving while during the spring season the concentration is lower but floe velocities are higher.

In general, the forces imposed by ice on offshore facilities are dependent on the following properties of the ice feature and the offshore structure:

Ice Feature Properties

- formation (level ice, pressure ridge, rubble pile, ice island),

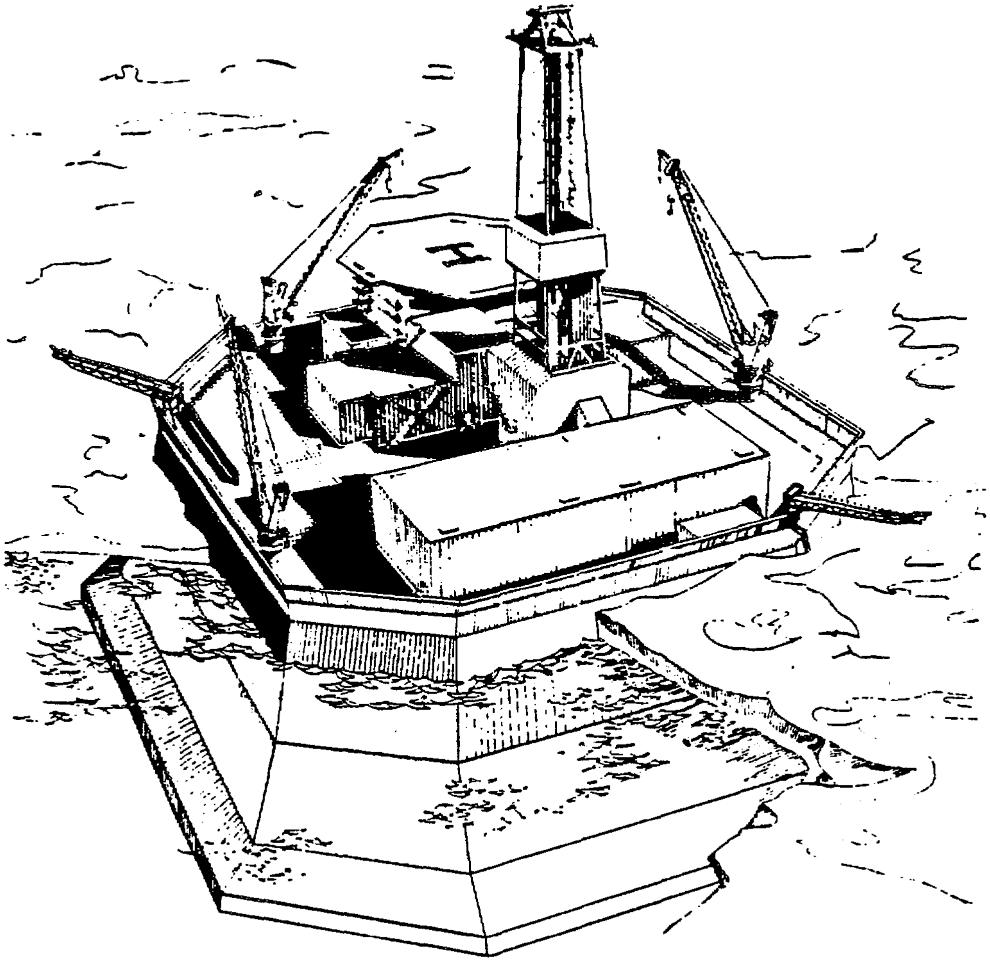

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Figure 3.2-2. Typical wide, vertical sided, bottom founded structure.

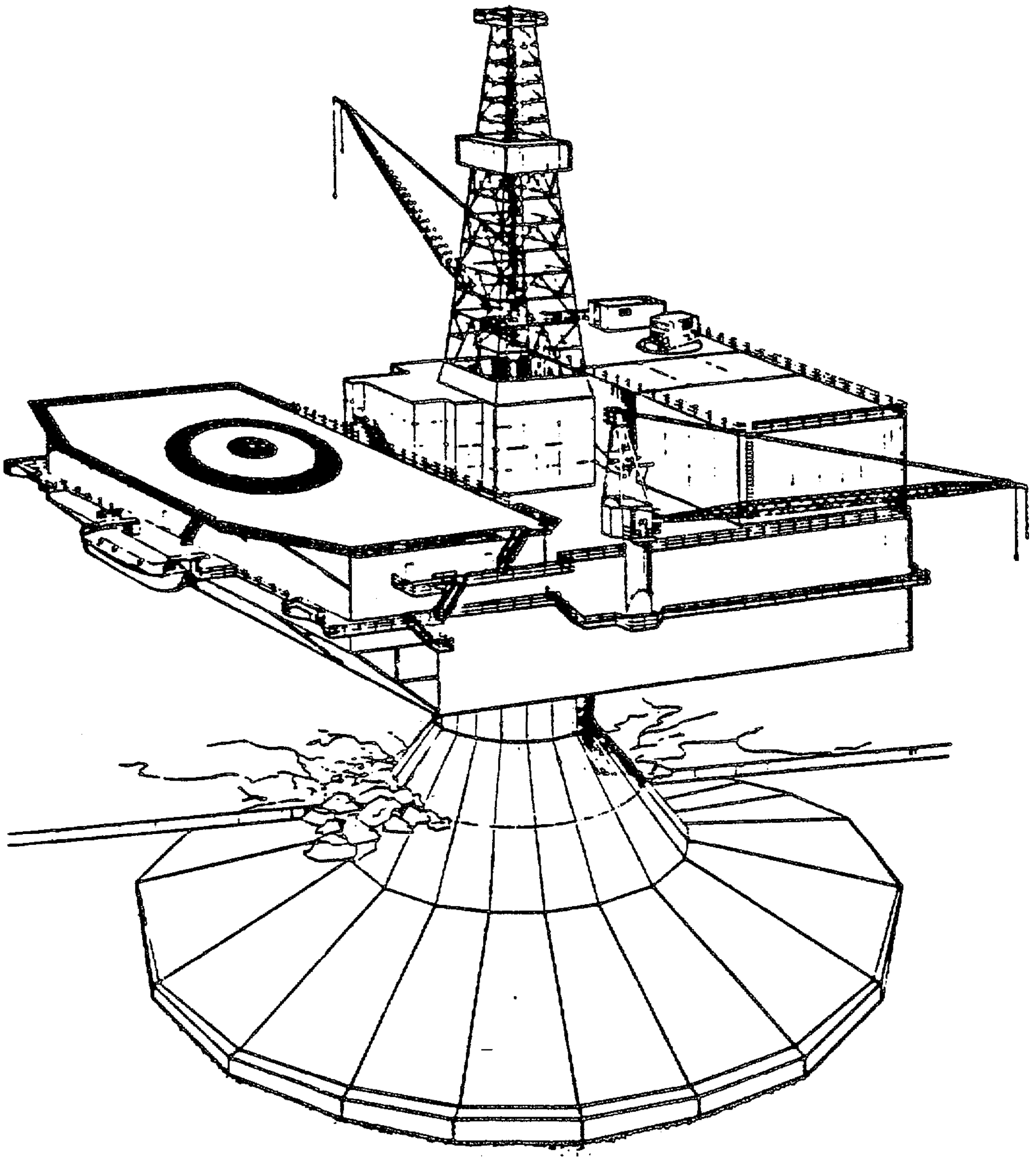

**Figure 3.2-3.** Typical conical bottom founded structure.

- consolidated thickness and areal extent,
- compressive flexural, tensile and shear strengths,
- temperature, age and salinity (strength functions),
- crystal structure,
- strain rate (function of velocity and dimensions),
- elastic modulus,
- chemical and physical impurities,
- kinetic energy, and
- availability of driving forces.

- Structure Properties
  - plan shape, dimensions, and water depth,
  - ice/structure interaction surface (vertical or conical),
  - ice/structure friction coefficient, and
  - structure elasticity and dynamic response characteristics.

The magnitude of the forces that a fixed production or exploration platform can experience as a result of direct interaction with an ice feature will depend on one of the following limitations: a) the maximum stress that develops as a result of the applicable mechanism causing complete failure and clearing of the feature, b) the maximum wind, current and pack ice driving force, and, c) the kinetic energy of the ice feature that must be dissipated during the ice/structure impact. These three limiting force conditions are referred to, respectively, as:

a) The Ice Strength Limit,
b) The Driving Force Limit, and
c) The Energy Limit.

Given an ice feature either possessing infinite kinetic energy or having an infinite driving force available, the maximum force that can be applied to the structure corresponds to the force causing failure and clearing of the ice. However, ice/structure interaction scenarios in which the ice feature driving force and kinetic energy are finite values may result in maximum applied forces that are less than the ice failure and clearing forces. For instance, it is readily understood that an ice floe cannot exert a sustained force on a rigid structure in excess of the force with which it is being pushed. However, even though a particular feature may be subject to minimal driving forces, at the instant of impact it may still exert on the structure a force higher than the driving force, though less than or equal to the ice failure load, if it possesses sufficient kinetic energy by_ virtue of its mass and velocity. In this case, the kinetic energy of the ice feature, including its added mass, is gradually dissipated as the structure progressively fails the advancing ice. The maximum contact force generated during the impact, however, can not exceed the force causing full failure of the ice feature.

The methods used for the determination of each of the three primary limiting ice force conditions on the structure configurations considered in this study are described below. They are based on theories which, for the most part, have not been substantiated by full scale tests. Considerable proprietary testing has been carried out which indicates that actual loads on a structure will be less than those indicated by the theories used.

It is recognized that many secondary ice failure phenomena, such as in-plane bending, rubble pile buildup (Good et al., 1984), and buckling, may, at times, effectively reduce ice loading on the platforms. These occurrences, however, do not represent the governing failure modes and thus are not considered further in this section. The special problem of potential ice island impact on a structure is treated separately in item d) below.

### a) The Ice Strength Limit

The geometry of the structure and the ice feature formation govern the failure mode during interaction of the ice. Applicable ice failure modes include:

- crushing,
- buckling,
- bending in the vertical plane,
- bending in the horizontal plane, and
- double-sided shear (along vertical planes).

A vertical-sided structure will cause ice to fail by crushing, buckling, shearing along vertical planes or bending in the horizontal plane, depending on the ice formation's characteristic dimension and the structure diameter. Conical structures generally induce vertical deflection of the ice feature, causing primary failure by bending. In instances where large adhesion bonding strengths of a stagnant ice floe to a conical structure exist, alternate failure modes may include crushing, buckling or double-sided shear along vertical planes. To reduce the chance of adhesion bonding to a structure, special low friction coatings similar to those used on icebreaker hulls are commonly employed.

Vertical-sided or near-cylindrical shapes are currently being used in the form of caisson retained islands and prefabricated, bottom founded structures in water depths up to approximately 21 m (70 ft). These concepts are classified as wide structures with high aspect ratios (the ratio of structure width to ice feature thickness). Narrow cylindrical shapes at the waterline are being considered for use in the form of monopod type designs. Conically-shaped structures are predominant as concepts proposed for the Beaufort transition zone because they cause large multi--year ridges to fail in bending rather than crushing. Ice force calculation methodology for cylindrical and conical structures based on the ice strength limit follows.

### 1) Cylindrical Structures

The theory of ice crushing on a cylindrical surface is a classic topic in the field of ice mechanics and accounts for the bulk of the research effort in this field over the last twenty-five years. However, the amount of field data applicable to the size of structures required for exploration and production operations in the deeper waters of the Beaufort Sea is minimal and, therefore, the validity of even the latest state-of-the-art theories remains largely unsupported. A complete review of this topic is outside the scope of this study and the reader is referred to Neill (1976) and Croasdale (1980) for further information.

Korzhavin (1962) prepared the early framework for solution of this problem with the empirical relationship:

$$F = I m k s_c h d$$

where: F = ice force in crushing on a vertical-sided structure;

I = indentation factor which is dependent on the aspect ratio (d/h) and which takes into account the three-dimensional effects of the ice stress field in front of the structure;

m = shape factor to account for the various plan shapes of ice indenters;

k = contact factor which accounts for the actual degree of ice/structure contact achieved at any instant of time;

$s_c$ = ice compressive strength;

h = ice thickness; and

d = characteristic structure dimension at the waterline (diameter or width).

Since that time, most of the research has been directed towards further defining the values of I, k and $s_c$. These three factors are interrelated in that they depend on many of the same parameters namely, aspect ratio, rate of loading, crystal structure and orientation, and ice temperature. The exact definition of the functional relationship among these parameters has so far gone unsolved by theoretical analysis because the fracture mechanism and failure criterion of ice, as a viscoelastic, anisotropic material, has not been fully established.

Plasticity theory, and its Lower-and-Upper-Bound Theorems, simplify the problem by assuming ice to be an isotropic, elastic-plastic material while neglecting the effect of contact dependence (Croasdale et al., 1977; Michel and Toussaint, 1977; Ralston, 1977b and 1978).

In-field and small scale ice force measurements have been conducted by many investigators including Frederking and Gold (1975), Michel and Toussaint (1977), Blenkarn (1970), Nevel et al. (1972), Schwarz et al. (1974), Saeki et al. (1984) and Croasdale et al. (1977), among others. Data from these measurements are of limited application to site specific. ice conditions and structure dimensions suitable for the Beaufort Sea. In general, though, ice strength has been shown to possess a strong dependence on loading rate and a possible dependence on aspect ratio (Croasdale, 1980) along with its known dependence on salinity and crystal orientation.

To simplify the preliminary design process and place all structural concepts on an equal design basis for cost estimate comparisons, an average, conservative ice compressive strength has been used, as given in Section 3.1.1. Ideally, design ice strengths should be selected based on test results for each specific structure and for each combination of ice thickness and velocity (winter and summer extremes) based on actual aspect ratio, temperature and strain rate combinations. However, the nature of this study does not warrant such an approach.

The shape factor, m, is defined as 1.0 for a flat indenter and 0.9 for a circular indenter. These values are in universal agreement among all references and have been used in this study.

Values for the contact factor, k, appear to range between 0.3 and 1.5. The value of k decreases towards 0.3 as the ice brittleness and strain rate increases and tends towards 1.0 as the ice ductility increases and strain rate decreases. The contact factor can be physically interpreted as an indication of the actual amount of ice/structure contact occurring in relation to the full area available for contact during continuous crushing episodes. For perfect and total contact, k equals 1.0 and may increase beyond 1.0 up to 1.5 during conditions of ice adfreeze to the structure. The contact factors used are concept specific and were selected on the basis of' ice movement rates and coverage, and structure size and shape.

The indentation factor, I, has received significant attention in the form of direct laboratory and field measurements and theoretical modeling. The following equation was first proposed by Afanas'ev et al. (1971) arid later shown by Neill (1976) to agree quite well with experimental test data by Allen (1970), Assur (1971) and Schwarz et al. (1974):

$$I = [1.0 + 5(h/d)]^{0.5}$$

Croasdale's et al. (1977) plasticity analysis, utilizing failure criteria developed basically for isotropic materials, results in indentation factors comparable to those proposed by Afanas'ev for aspect ratios above approximately 3.0 and may be considered applicable for granular ice (Croasdale and Pearson, 1984). Ralston (1978) applied the plasticity theory by fully generalizing the von Mises yield criterion to account for material anisotropicity, pressure sensitivity and unequal strengths in tension and compression. He demonstrated that this approach leads to satisfactory agreement with the laboratory test data of Michel and Toussaint

(1977) for two-dimensional in-plane loading of freshwater, columnar-grained, laboratory grown ice at -10"C. Three-dimensional aspects, continuous crushing phenomena and plastic buckling, all known to have a reducing effect on the indentation value, were not addressed in Ralston's analysis and the results should be used basically as a qualitative interpretation of large scale ice interactions.

Figure 3.2-4 shows the difference among the theoretical relationships for indentation factors as proposed by Afanas'ev et al., Croasdale et al., and Ralston. Ralston's analysis, resulting in the highest indentation factors, has been used for this study as a conservative approach in the preliminary design phase.

In calculating the crushing force on a cylindrically shaped structure using Korzhavin's formula, the ice thickness, h, has been taken as the full level ice or ice island thickness or as the consolidated thickness for pressure ridges. The unconsolidated rubble portion of the ridge feature is assumed to crush or shear off without applying load to the structure and only has a significant effect on clearing mechanisms or rubble build-up for wide, shallow water structures. Isolated floes with embedded ridges may occasionally fail at less than the full crushing force by in-plane bending or double-s"ided shearing mechanisms assuming sufficient driving force is available. Experience indicates, however, that these alternate failure mechanisms are the exception and not the rule, and thus do not represent the desired upper limit for design

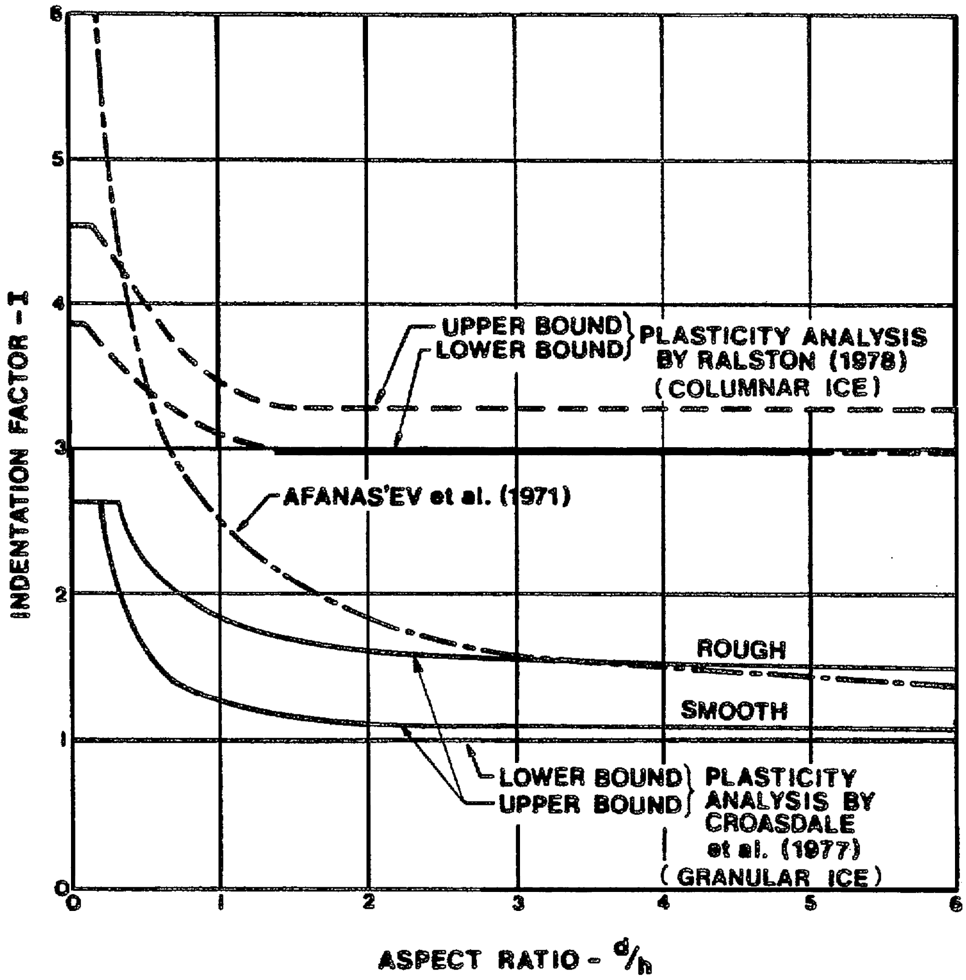

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Figure 3.2-4. Comparison of indentation factors.

purposes.

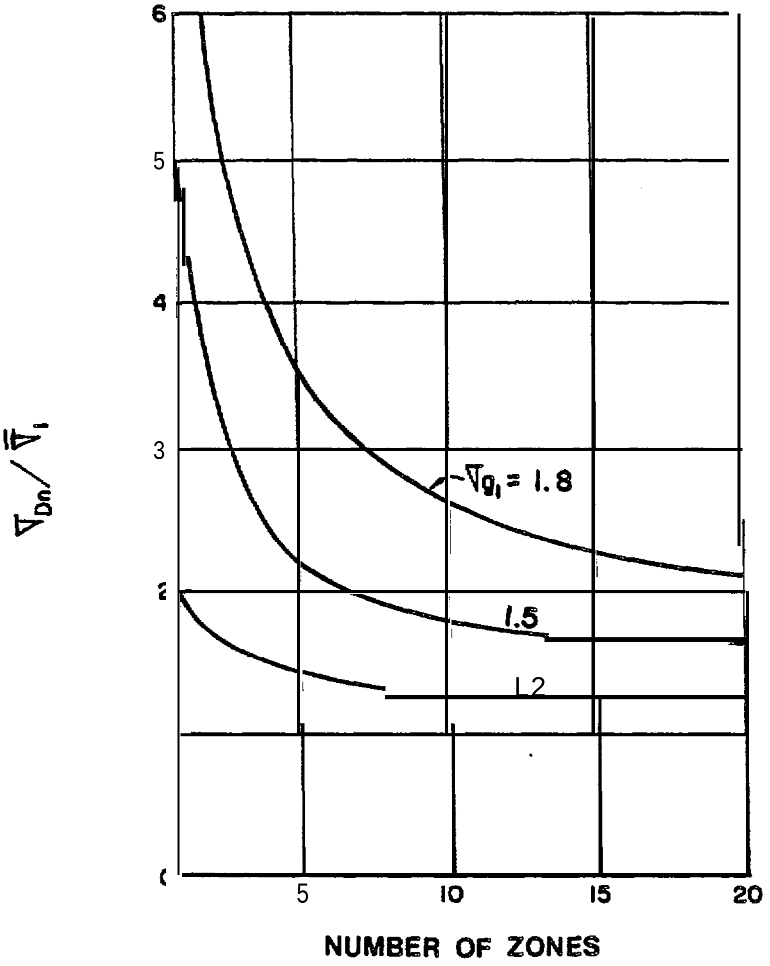
Research on ice crushing theory for wide structures by Kry (1978) indicates a possible reduction in global ice load from that resulting from Korzhavin's formula. Kry proposed a crushing model where the interaction width is divided into statistically independent zones, thus allowing calculation of the statistical influence of nonsimultaneous failures across the entire structure. The basis for the theory lies in the intuitive recognition that, given a pressure distribution for each zone (assuming each acts independently), the simultaneous peak pressure average across all zones will be less than the peak pressure (given by Korzhavin's formula) for any single zone. Thus, this approach relies upon the-degree to which it can be proven that single zone failures do not influence adjacent zones and also upon the selection of a zone width to ensure truly independent failure mechanisms.

Kry (1980) has indicated that the lower limit for a single zone width corresponds to an aspect ratio of four to five, i.e., a zone width equal to four to five times the ice thickness. This has been based on experimental indentation tests indicating the point at which edge effects no longer contribute to the indentation stress and also on field observations of failed sheet ice on gravel islands. Thus, for example, a typical caisson retained island may represent a width of up to fifteen zones in landfast annual ice.

Kry's (1978) statistical approach is based on a log-normal probability distribution and the results are illustrated in Figure 3.2-5 for three values of the single zone geometric standard deviation at an arbitrary instantaneous local design ice pressure probability of being exceeded equal to 3.0 x $10^{-5}$ (Kry, 1980). The standard deviation values indicate the level of variation of ice forces in one zone and no variation at all would correspond to a value of 1.0. Figure 3.2-5 indicates that the largest statistical reduction in design stress occurs for the first few number of zones and that greatly increasing the number of zones does not result in proportional reductions. Also, the greater the standard deviation for a single zone, the larger is the magnitude of the reduction (Kry, 1980).

Although some recent proprietary large scale crushing tests and direct field measurements of ice stresses around gravel islands have been carried out, Kry's statistical approach remains unproven. While it is anticipated that future research will confirm Kry's approach for brittle failure interactions, this statistical reduction for non-simultaneous crushing phenomena has not been applied for the preliminary designs prepared for this study in order to achieve conservative results.

Dynamic aspects of ice/structure interactions have been known to influence ice failure mechanisms. Maattanen (1983) investigated the influences of both the ice and structure properties on the ice



$\sigma_{Dn}$ = Design ice stress

$\bar{\sigma}_1$ = Single zone statistical median stress

$\sigma_{g1}$ = Single zone geometric standard deviation

Adapted from: Kry, 1980

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Figure 3.2-5. Design ice stresses versus the number of zones in a wide structure and the single-zone stress variations.

forces, crushing frequency, damping effects and self-excited vibrations of the continuous crushing phenomenon. The platforms under consideration are assumed sufficiently rigid to preclude significant crushing effects resulting from dynamic response.

2) Conical Structures

Conical structures cause ice features to vertically bend and fail by flexural mechanisms. Bending failure has been studied both analytically (Afanas'ev et al., 1971; Bertha and Danys, 1975; Ralston, 1977a) and experimentally (Sorensen, 1977; Edwards and Croasdale, 1976; Pearce and Strickland, 1979; Saeki et al., 1979; Frederking and Schwarz, 1982), with the major emphasis on determining the sequence of failure mechanisms and identifying all feasible failure interaction modes. Bending failure loads are comprised of separate components for failure of the ice and for clearing the ice feature past the structure. Level ice and pressure ridges exhibit different failure mechanisms during interaction with a conical structure and are discussed separately below.

Level Ice

Excellent agreement between model tests conducted on level ice interacting with a sloping surface (Edwards and Croasdale, 1976) and an analytical plastic description of the phenomenon has been achieved by Ralston (1977a) with the following equations:

$$R_H = [A_1 s_f h^2 + A_2 P_w g\ h\ D^2 + A_3 P_w g\ h_R (D^2 - D_T^2)]\ A_4$$

$$‘_v = B_1 R_H + B2\ P_w g\ h_R (D^2 - D_T 2,$$

where: $R_H$ = horizontal force on cone;

$‘_v$ = vertical force on cone;

$’_f$ = **flexural** strength of ice sheet;

$P_w g$ = weight density of water;

h = ice sheet thickness;

$’_R$ = ice ride-up thickness;

D = waterline diameter of conical shape;

$’_T$ = top diameter of cone;

Al, A2 = f(D, $s_f$, h);

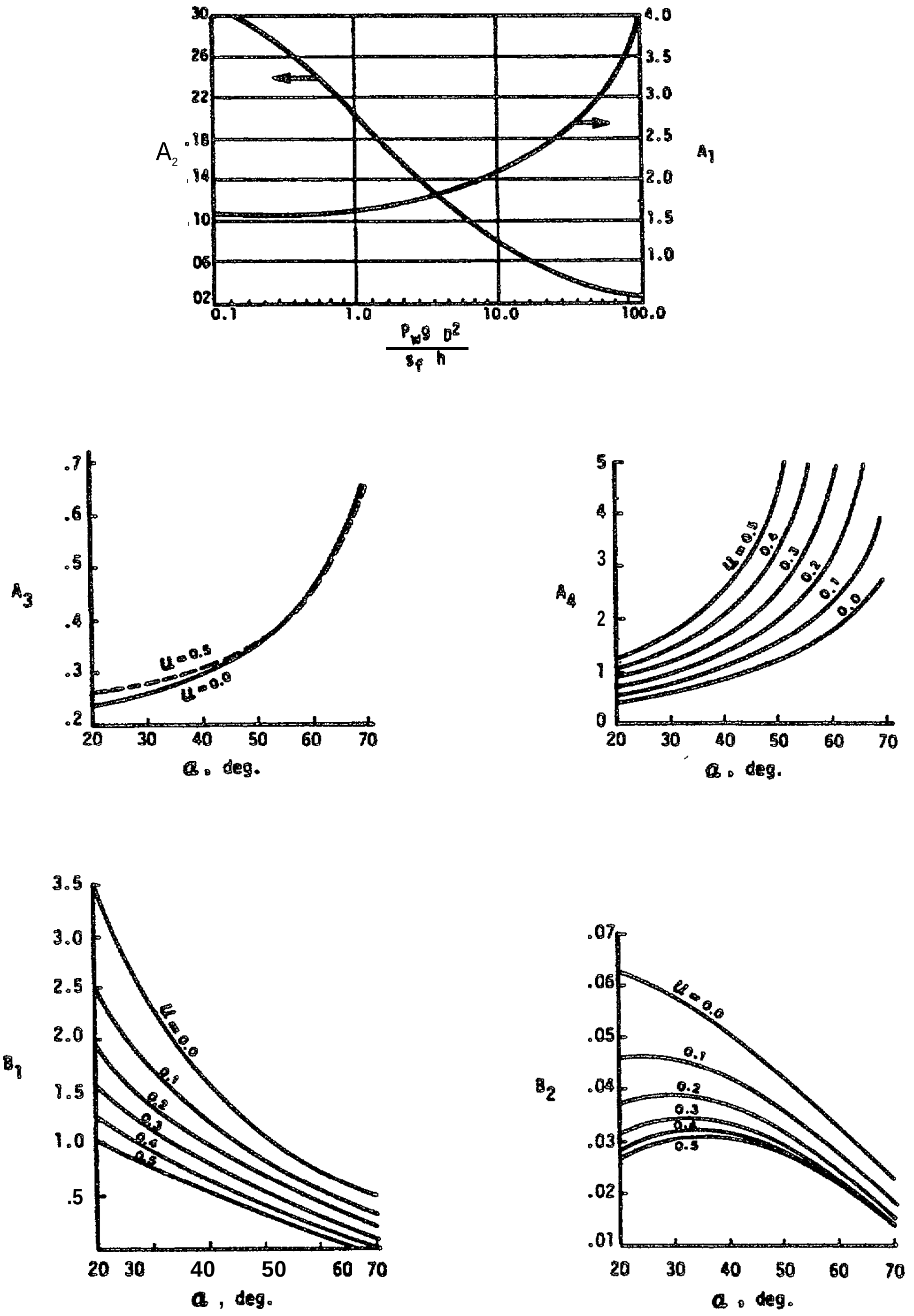
$A_3$, A4, $B_1$, B2 = f(a,u);

a = cone angle measured from horizontal; and

u = ice-structure friction coefficient.

Graphs for $A_1$, $A_2$, A3, A4, $B_1$ and B2 are given in Figure 3.2-6.

In this approach, Ralston idealizes the floating ice sheet as an elastic-perfectly plastic plate supported by an elastic-perfectly plastic foundation, using a pure bending failure criterion. The first two terms of the $R_H$ equation account for the mechanism of flexurally failing the advancing ice sheet, while the third term accounts for the clearing of the broken ice pieces over or around the cone’s surface. The analysis used in developing these equations follows the approach of an upper bound determination using plastic



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Adapted from: API Bul 2N , 1982

Figure 3.2-6. Ice force coefficients for plastic analysis.

limit theory.

The sequence of failure events begins with a single radial crack propagating from the center of the structure into the advancing ice sheet. This is followed by additional radial crack formations as shown in Figure 3.2-7. Next, circumferential cracks form at the characteristic distance from the structure (determined by ice thickness and strength) and the individual ice pieces are forced to ride up the structure's surface by the advancing sheet behind them. Peak loads coincide with the formation of the radial and circumferential cracks and are applied in a cyclic nature with minimum forces correlating to the ice ride-up components (Pearce and Strickland, 1979).

A review of currently available failure theories for conical structures and a comparison of the various formulas can be found in Croasdale (1980) and Neill (1976). Ralston's method consistently predicts the largest total ice force for narrow, medium and wide structures, and thus seems to provide the desired upper limit bound for preliminary design purposes.

### Ridge Formations

First-year ridges and rubble fields in the landfast zone and multi-year ridges in the Stamuki zone will impose the greatest ice forces (excluding ice islands) on offshore structures in the Beaufort

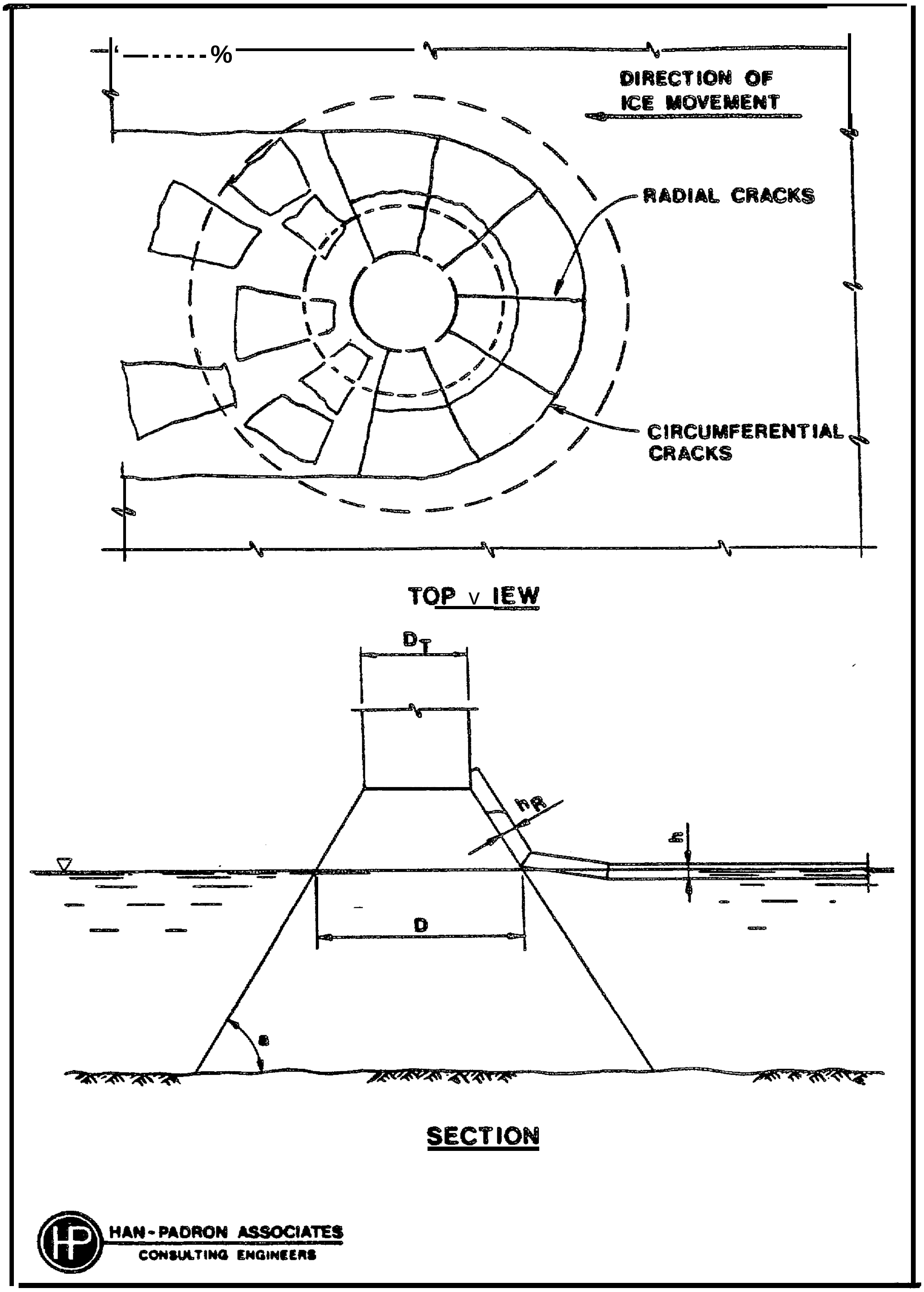


Figure 3.2-7. Ice sheet failure against a conical structure.

Sea. The physical and chemical properties of pressure ridges and the processes involved in their formation are discussed in Section 3.1.1.

The analytical work to date (Croasdale, 1975; Ralston, 1977a; Bertha and Stenning, 1979) has assumed a ridge formation to act as an elastic beam on an elastic foundation (Hetenyi, 1946). The only known published experimental data on ice ridge failure mechanisms is by Lewis and Croasdale (1978). The analytical procedure of Croasdale (1975 ) and Ralston (1977a) summarized by Croasdale (1980) follows.

Assuming the consolidated ridge is uniform in cross-section, infinite in length and floating on an elastic foundation of water, the vertical force required to form the initial center crack of the ridge is given by:

$$R_{V1} = \frac{4\ I\ s_f}{Y_t\ l}$$

where: I = ridge cross-section moment of inertia;

$'_f$ = ice flexural strength;

$'_t$ = distance from the neutral axis to the top of the ridge (tension surface); and

l = ridge characteristic length on an elastic foundation, given as:

$$l = (4\ E\ I\ /\ P_w g\ b)^{0.25}$$

where: E = ice elastic modulus;

$P_w g$ = weight density of water; and

b = ridge width.

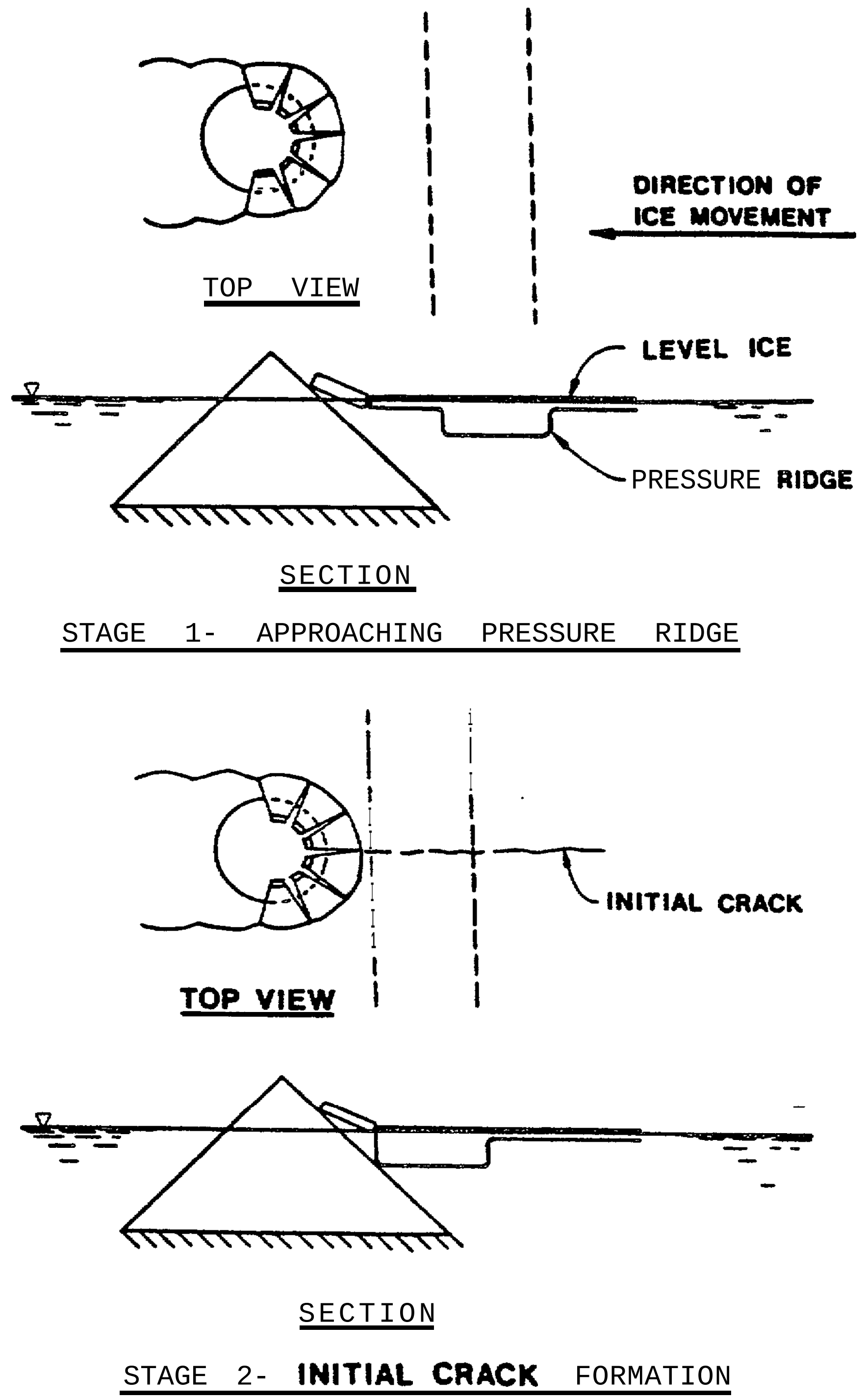
Although the ridge is broken with the formation of the center crack, it is not able to clear around a conical structure until secondary hinge cracks form and allow substantial rotation of the broken pieces. The mechanisms required to fail and clear the ridge feature around a conical structure are shown in stages in Figures 3.2-8, 3.2-9 and 3.2-10, after experimental results by Lewis and Croasdale (1978). The vertical force corresponding to the simultaneous failure of two semi-infinite floating ice beams is:

$$R_{V2} = \frac{6.17\ I\ s_f}{Y_b\ l}$$

where: $Y_b$ = distance from the neutral axis to the bottom of the ridge (tension surface).

Simultaneous hinge crack formation almost always results in a higher load than formation of the initial crack. Although simultaneous crack occurrence depends on a uniform ridge cross-section and strength, an unlikely probability, it is still considered a prudent approach in view of the following two circumstances.

First, the above equations do not consider the effects of the surrounding ice sheet which may increase the required failure forces for the ridge, especially in situations where the ice sheet is sizable in relation to the consolidated ridge thickness. This phenomenon is suspected to be the cause of the large discrepancies



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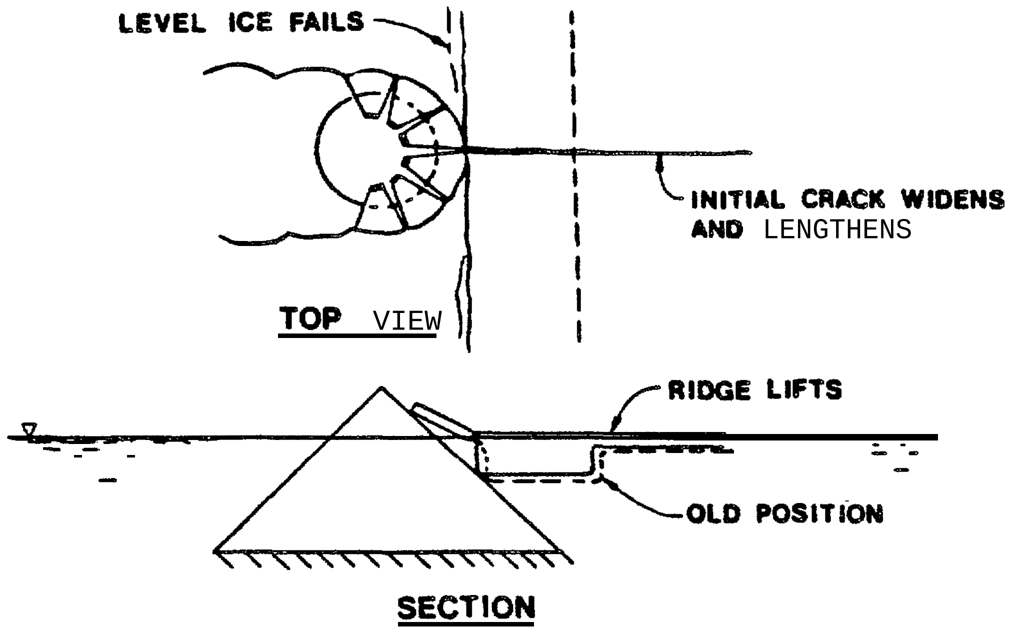
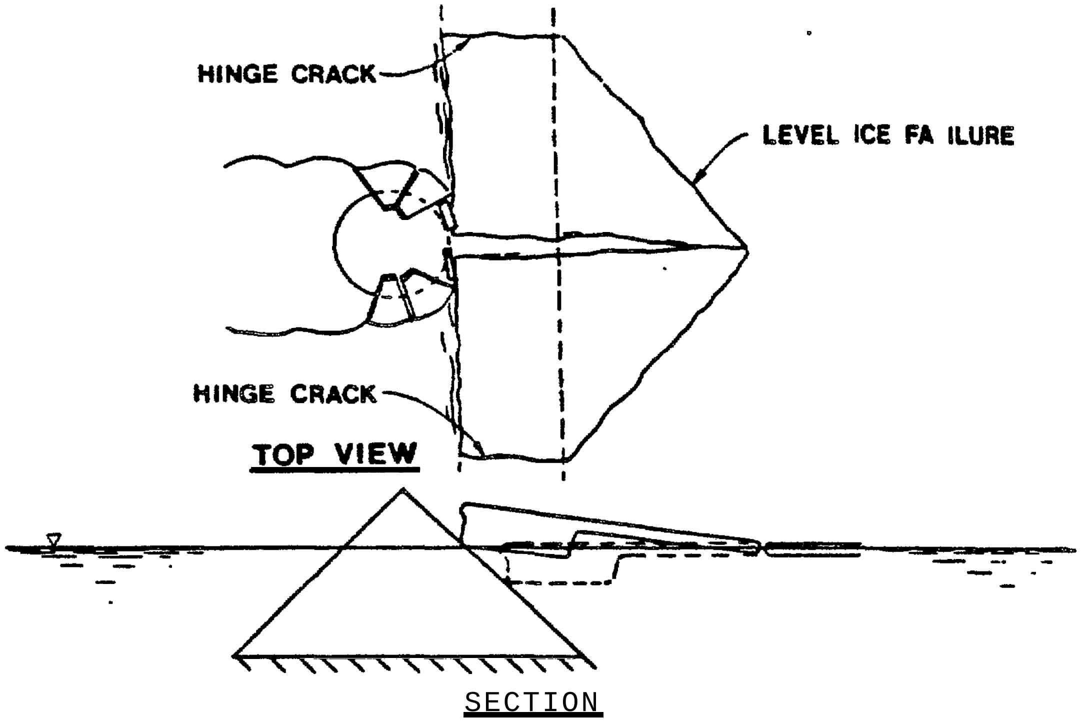
Adapted from: Lewis and Croasdale, 1978

Figure 3.2-8. Pressure ridge failure mechanism.



**STAGE 3- LEVEL ICE FAILS AT LEADING EDGE AS RIDGE LIFTS**



**STAGE 4 - SECONDARY HINGE CRACKS AND LEVEL ICE FAILURE**

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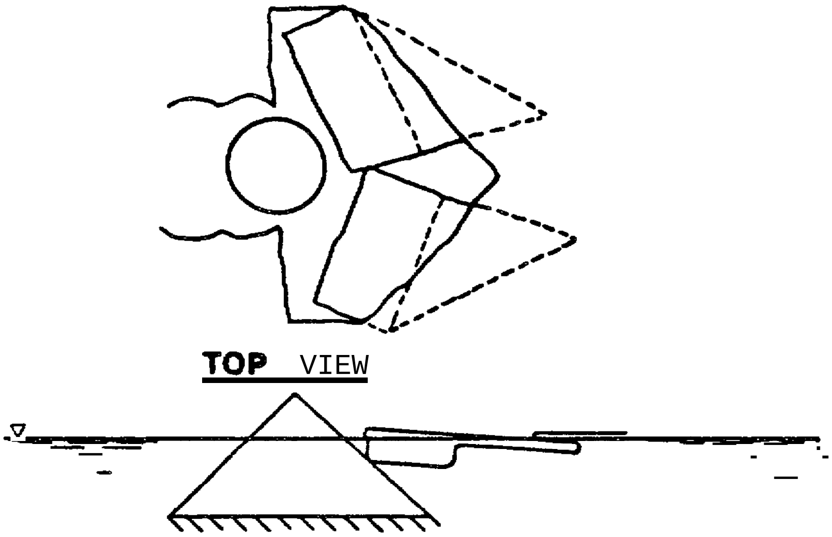
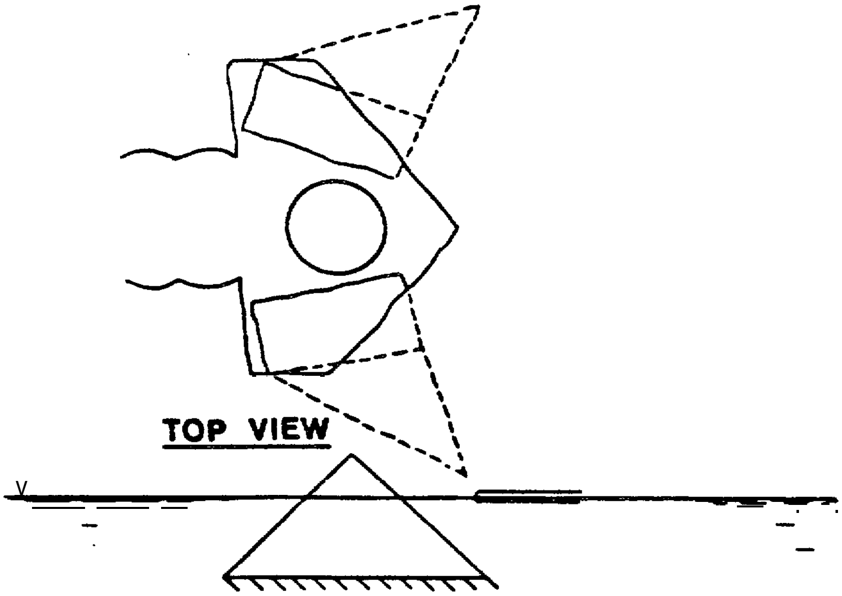
Adapted from: Lewis and Croasdale, 1978

Figure 3.2-9. Pressure ridge failure mechanism (continued).



STAGE 5- BROKEN **RIDGE** HALVES SLIDE **DOWN** FACE **OF** CONE **UNDER** UNBROKEN LEVEL ICE



STAGE 6- BROKEN **RIDGE** HALVES ARE **FULLY** CLEARED AROUND STRUCTURE

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Adapted from: Lewis and Crossdale, 1978

**Figure** 3.2-10. Pressure ridge failure mechanism (continued).

between experiment and theory for the smaller ridge size in Lewis and Croasdale's (1978) work (Croasdale, 1980).

Secondly, stemming from the elastic beam analogy work of Hetenyi (1946), Ralston (1977a) proposes that extension of the elastic model to beams of finite length leads to the prediction that vertical forces for flexural failure will increase with decreasing ridge length within a predictable range of ridge lengths. Hence, it is possible that, unless alternate failure or clearing interactions are introduced, shorter ridges may exert greater forces on the structure than longer ridges. Since no further information is available at this time, the simultaneous formation of hinge cracks is considered a justifiable assumption.

Based on the assumed strength of the unconsolidated rubble portion of the ridge (Prodanovic, 1979), the load required to crush or shear through the rubble mound is considerably less than the peak force required to fail and clear the consolidated ridge portion. Since the peak loads from each failure mechanism occur at different stages of the ridge passing, the controlling design load is that which corresponds to the consolidated ridge failure.

The above ridge formulas represent only the vertical force required to cause failure of the ridge, the resulting horizontal force is solely dependent on the slope angle, a, and the coefficient of friction, u, at the ice/structure interface. The relationship between the vertical force, $R_V$, and the horizontal force, $R_H$, is given by:

$$R_H = R_v\left(\frac{\sin a + u \cos a}{\cos a - u \sin a}\right)$$

A graphical representation of the above equation is shown in Figure 3.2-11 as the slope angle, a (measured from the horizontal), is plotted against the horizontal to vertical force ratio as a function of the interface coefficient of friction. Friction experiments between sea ice and commonly used offshore construction materials have recently been conducted by Saeki et al. (1984) and Tusima and Tabata (1979). The strong dependence of the horizontal load applied to the structure on both the interface angle and frictional coefficient is readily evident. It should be remembered that the vertical load causing failure of the design ridge is constant, irrespective of the conical structure's geometry or surface material.

Proper precautions must be taken to assure that stagnant ice floes do not adfreeze to a conical structure that relies on flexural failure mechanisms to clear the ice. If such a condition occurs, the bond force may surpass the force required for flexural failure of the ice and may approach the much higher force required for crushing failure (Gershunov, 1984). Low friction coatings and heat tracing systems, along with proper ice management, may be used to ensure that adfreeze conditions do not occur.

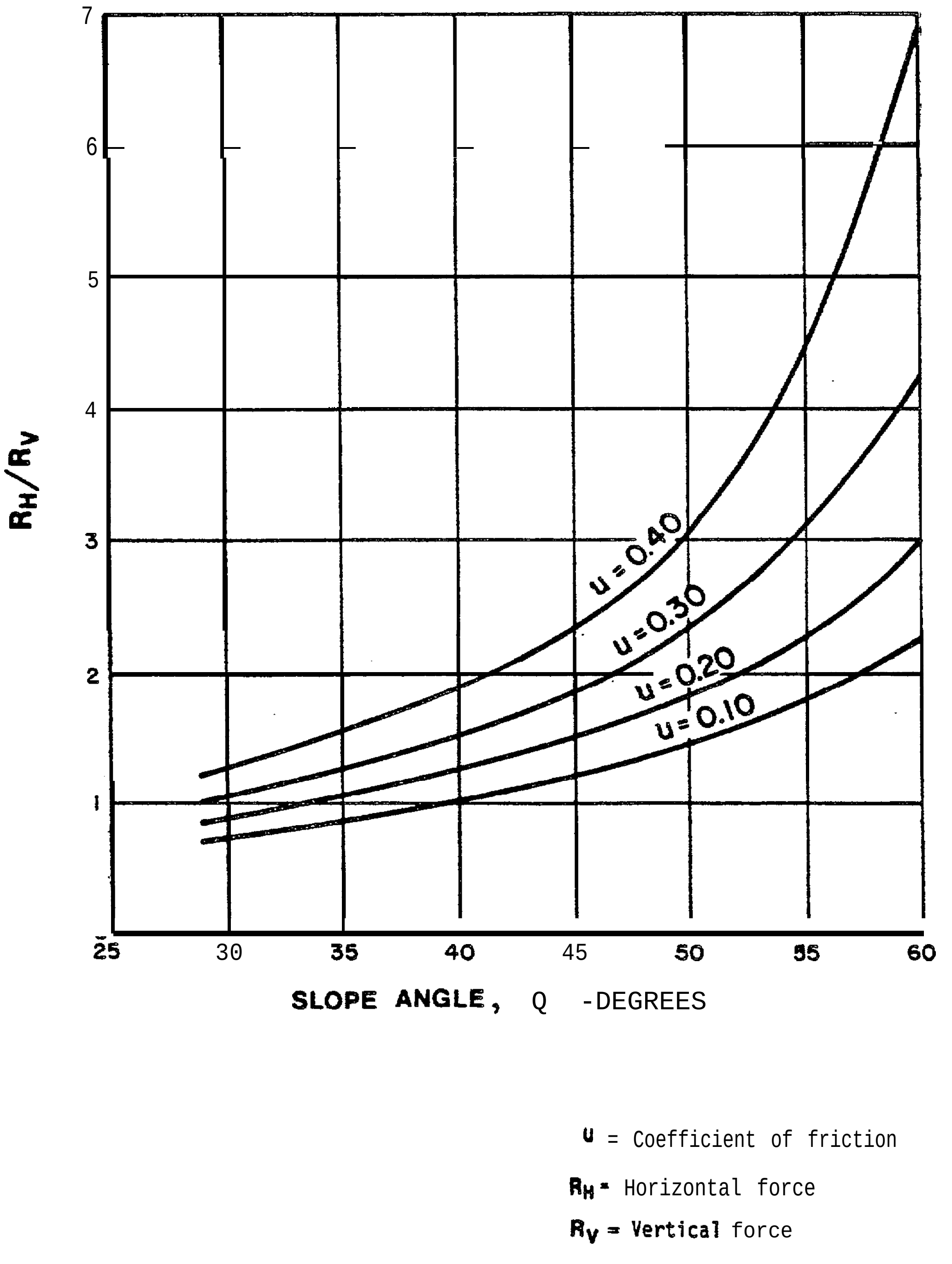

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**Figure** 3.2-11. Relationship of ridge induced horizontal load to vertical ridge failure load as a function of slope angle and coefficient of friction.

The driving force on an ice floe of finite dimensions is composed of the wind and current drag forces and the surrounding pack ice forces. The driving force limitation has been considered as normally relevant only in the determination of governing ice loads for large, wintertime multi-year floes interacting with wide structures located in the transition ice zone. Vivatrat and Kreider (1981) and Croasdale (1984) have presented in-depth discussions on the applicability of driving force calculations for Beaufort Sea offshore structures.

The expression for the total driving force, F, on a floating ice feature takes the form:

$$F = C_{10}\ Pa\ V_a^2\ L\ B + 0.5\ C_w\ P_w\ V_w^2\ L\ B + p\ B$$

where: $C_{10}$ = wind drag coefficient at the 10 m (33 ft) elevation level;

$C_w$ = water (current) drag coefficient;

$Pa$ = air density;

$P_w$ = water density;

$V_a$ = air (wind) speed;

$V_w$ = water (current) speed;

$p$ = average pack ice force across width of floe;

L = length of flow; and

B = width of floe.

The first term represents the wind drag on the ice floe, the second term the current drag and the third term the pack ice force. The greatest uncertainties lie in the applicable wind drag coefficient, $C_{10}$, and the average pack ice force, p.

Danys (1977) gathered values of $C_{10}$ for various snow surfaces from investigations performed between 1936 and 1973 and recommends an average value of 0.0022 for unridged rough ice. Fewer experimental results are available for drag coefficients over ridged ice. Smith and Banke (1973) suggested multiplying the level ice drag coefficient by a correction factor of 2.0 to account for additional drag on ridge formations. Arya (1973) suggested a correction factor of approximately 1.4. For preliminary design purposes, a $C_{10}$ correction factor of 1.5, has been applied to Danys' recommended average unridged rough ice value for the ridged ice conditions expected in the study area.

The limiting force that the surrounding pack ice can transmit to the ice floe is generally believed to correspond to the force required to form pressure ridges in the pack ice cover. Pack ice strength, ridge formation forces, and force limitations have been discussed by Vivatrat and Kreider (1981), Croasdale (1984), Mellor (1983), Nevel (1983), Pritchard (1977), Hibler (1980), Rothrock (1975), and Parmerter and Coon (1973). Local ridge building forces have been shown to vary from 146 to 730 kN per meter (10,000 to 50,000 lb/ft) of width for 2 m (6.5 ft) thick level ice (Vivatrat and Kreider, 1981). Croasdale (1984) recommended a range of 20 to 350 $kNm^{-1}$ (1,370 to 24,000 lb/ft) based on information from a variety of sources covering a full range of level ice thicknesses. For purposes of this study, an average value of 290 $kNm^{-1}$ (20,000 lb/ft) pack ice force has been assumed to apply over the full ice feature width for order-of-magnitude calculations of driving forces.

In general, the calculated driving force limit resulted in lower loads than the ice-strength forces only for ice/structure contact scenarios in which multi-year ridges or ice islands are assumed to be lodged against a wide structure. This condition may occur for winter floes which move slowly, however, the higher open-water, summer floe velocities often result in floe kinetic energies yielding much higher forces during energy dissipating collisions, as will be discussed in the next topic. Therefore, in the preliminary design of year-round production structures, driving force limitations only rarely provided the design load condition.

### c) The Energy Limit

Individual ice floes drifting in the Beaufort Sea possess kinetic energy by virtue of their mass and drift velocities. Upon collision with an offshore structure, this kinetic energy is dissipated by both the deflection of the structure and by the progressive failure, lifting, rotating and elastic deforming of the ice feature, along with hydrodynamic effects. This conservation of energy approach may be summarized as:

$$KE + KE_{df} = U_f + U_s$$

where: $KE$ = kinetic energy of the floe before collision;

$KE_{df}$ = kinetic energy added to the floe by driving forces during the collision process;

$U_f$ = energy absorbed by the floe during the collision process; and

$U_s$ = energy absorbed by the structure during the collision process.

If the kinetic energy is sufficiently low, such that the ice floe comes to rest before the entire width of the structure is embedded in the floe, then the resulting maximum force will be less than the limit ice strength force and will provide the design load condition, providing the environmental driving force is less. The maximum force on the structure will occur just before the floe comes to rest (when the contact width is greatest). For large kinetic energies that cause full structure penetration into the floe, the design load condition is limited to the ice strength failure load. Processes for the absorption of kinetic energy during structure collisions with level ice, ridges, icebergs and ice islands have been investigated by Russell et al. (1983), Gerwick et al. (1984), Cammaert and Wong (1983), Croteau et al. (1984), Sodhi and Morris (1984), Croteau (1983), Cammaert and Tsinker (1981), and Bercha and Stenning (1979), among others.

As a conservative simplification for offshore structure preliminary design it has been assumed that the kinetic energy applied by driving forces during collision, $KE_{df}$, and the kinetic energy absorbed by the structure during collision, Us are small and can be neglected in the energy balance equation. As a further simplification, only the crushing energy dissipated by the structure penetration into the ice feature was considered as contributing to Us; rotation and lifting of the ice feature and hydrodynamic effects being ignored. In the case of conically shaped structures, energy absorbed by lifting of the ice feature as it rides up the sloped walls may indeed represent a significant percentage of the total energy dissipation, however, by omitting this source of energy dissipation, a desired upper bound impact force is obtained for preliminary design purposes. The previous energy equation may thus be expressed as:

$$0.5(M_f + M_h)V^2 = \int_0^{x=XM} (F)\, dx$$

where:
$M_f$ = mass of the floe;
$M_h$ = hydrodynamic or added mass of the floe by virtue of its movement in a water medium;
V = floe drift velocity;

$x$ = structure penetration into the floe;

$XM$ = maximum structure penetration; and,

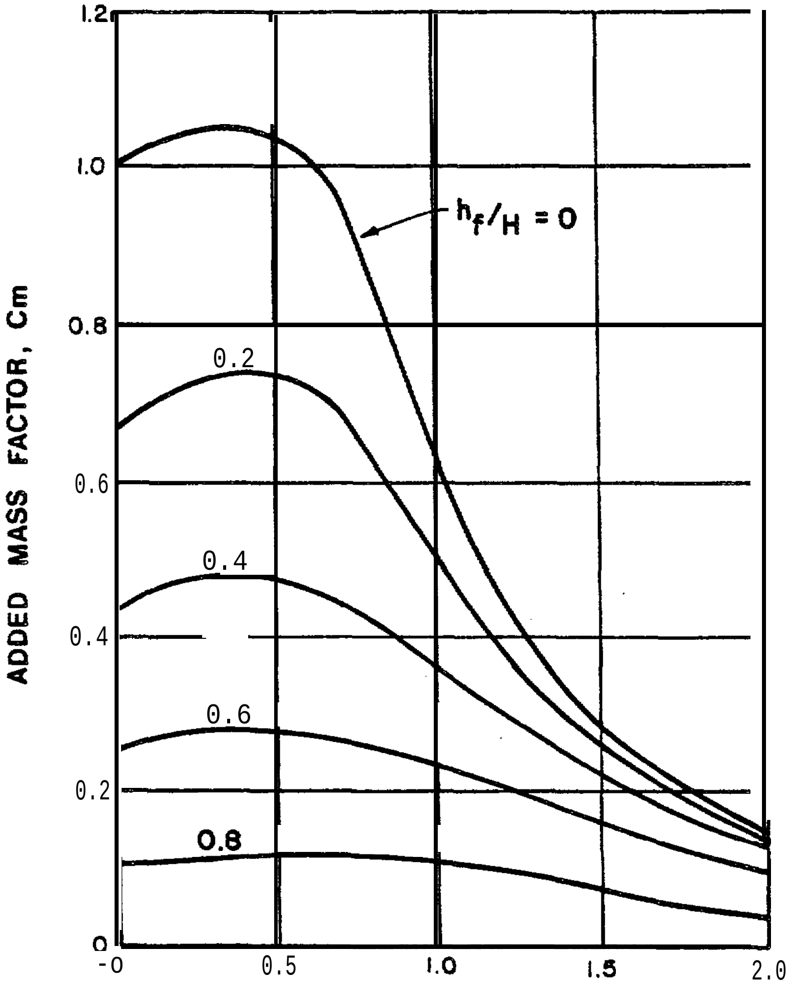
$F = I\ m\ k\ S_c\ h\ d_x$; where all parameters are defined as in the ice strength limit topic except that $d_x$ is the structure width corresponding to the penetration, $x$.

The added mass of the ice floe, $M_h$, corresponds to the hydrodynamic force component acting on the decelerating ice mass. Numerous investigations have been performed to determine the effective added mass of tankers and cargo vessels for the advancement of fender system and pier design procedures. These investigations, however, were targeted towards near cylindrical shapes, and their applicability to the wide range of irregular ice feature shapes is not readily apparent. Luk (1983) has applied long water wave theory to the calculation of added masses for flat floes with thicknesses much less than the areal dimensions. Luk's recommended added mass factors, $C_m$, shown in Figure 3.2-12, have been used to obtain hydrodynamic mass values from the equation:

$$M_h = C_m \times M_f$$

The added mass factors, Cm, are given as a function of the frequency parameter for a circular floe with the following defined terms:

$w$ = angular frequency of floe motion;



Adapted from: Luk, 1983

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Figure 3.2-12. Added mass coefficient versus circular floe frequency parameter for surge motion.

$r$ = radius of the floe;

$g$ = acceleration of gravity:

$H$ = water depth; and,

$h_f$ = water depth between bottom of floe and seabed.

From the shape of the curves in Figure 3.2-12 it can be seen that as the clearance between the ice floe and the seabed decreases, the hydrodynamic added mass increases. This phenomenon has also been observed in the ship added mass investigations referred to above.

For thick ice features in shallow water, an alternate energy absorbing scenario may require consideration, that of an ice/soil berm interaction. Dunwoody et al. (1984) has conducted a model study to determine some of the energy absorbing characteristics of sand berms interacting with variably configured and stiffened ice floes. For purposes of this study, it has been assumed that structures configured to rest on built-up berms may be subject to maximum ice floes, where applicable, with consolidated drafts up to five feet larger than the structure draft. It is assumed that floes with consolidated drafts greater than this value, but less than or equal to the water depth, will ground on the soil berm.

### d) Ice Islands

Ice islands represent a unique and severe loading threat to year-round production facilities located in the Beaufort Sea study region and require special consideration. Ice islands are known to originate from the ice shelves along the northern coast of Ellesmere Island, where pieces occasionally break-off and join the polar pack ice. Once within the Beaufort Gyre, the islands move under the influence of ocean currents, wind, pack ice pressures and Coriolis acceleration. The possibility exists for an ice island to exit from the polar pack and to pass through the southern Beaufort Sea study region.

During the winter, the island would be embedded in the slow moving, high ice concentration of multi-year floes. The continuous crushing of advancing ice features will cushion island interactions with offshore structures and probably bring the island feature to rest against the structure. In this case, the maximum force applied to the structure will result from driving forces acting on the island and the surrounding accumulated pack ice. These forces consist of the environmental effects applied directly to the floe and the average ridge building pressures applied across the entire island width, as discussed in b) above. Eventually, the island will probably rotate about the structure and continue on its journey.

A probably more severe interaction scenario can occur when the ice island enters the study area during the summer, open water season. In this case, an individual ice island could have a relatively high drift velocity with resultant extremely high kinetic energy that must be dissipated during a collision with a permanent offshore facility.

As an illustration of the magnitude of the ice island impact problem, the impact force on a conical production structure in 60 m (200 ft) water depth has been investigated for both the design multi-year ice feature defined in Section 3.1.1 d) and an ice island 50 m (165 ft) thick and 40 x 40 km (25 x 25 mi) in extent. The maximum horizontal ice strength limit force applied to the structure by impact with the design multi-year ice feature is approximately 670 MN (150,000,000 lbs). The ice island can impose a maximum ice strength limit force of approximately 54,000 MN (12,000,000,000 lbs) to the same structure. For a wintertime interaction scenario, with the ice island lodged against the structure in a heavy multi-year ice concentration, the driving forces may accumulate up to 24,000 MN (5,400,000,000 lbs), less than half of the ice strength limit force. *However,* if the same ice island is drifting with a velocity of 1.0 mps (2.0 knots) during the open water season, the structure will have to penetrate the ice island a distance of over 900 m (3,000 ft) to completely absorb the kinetic energy. This amount of penetration results in the energy limit force equaling the ice strength limit force, thus representing the design force. Hence, the summer impact ice island force is approximately eighty times the design multi-year ice feature force for this example.

The above example makes it obvious that it is not reasonable to simply design offshore structures in the study area for an ice island impact, which represents essentially a "worst possible event," without evaluating the probability of occurrence of such an event during the twenty or so years that the structure will be in place and the economic consequences of the event. Research is presently under way to define the probability of an ice island encounter (Sackinger et al., 1984; Sackinger and Stringer, 1983). Also, probability assessments for island and floe energies and ice pressure and force distributions have been presented by Marcellus and Roth (1982), Vivatrat and Slomski (1983), Dunwoody (1983), Croasdale and Person (1984), Bertha and Stenning (1979), and Kry (1978). However, a much larger data base must be developed before final designs can be reasonably based on a probability approach. Also to be considered in the probability assessment is the possibility of redirecting a threatening ice island. Any such possibility would probably be feasible only for an open water scenario. Methods of ice management are currently being investigated and tested for icebergs along the eastern Canadian Coast and it may be possible to employ similar procedures on smaller sized ice islands in the summer Beaufort Sea.

For purposes of this study, it has been assumed that the probability of an ice island encounter with a production structure is sufficiently low for it not to be considered as a design loading condition. Since large ice islands can be readily tracked, it is assumed that sufficient advance warning of a possible encounter will be available to permit the shutdown of production, disconnection of flowlines and evacuation of personnel so that a collision and loss of the structure will not result in loss of life or catastrophic damage to the environment.

### 3.2.2 Wave Forces

Exploration and production platforms envisaged for the Beaufort Sea study area range from floating drillships to deepwater, bottom-founded gravity platforms. Floating exploration vessels need not be designed to remain on station in the most severe wave conditions since they are equipped to rapidly stop drilling operations and disconnect from their moorings if necessary. Fixed exploration and production platforms, however, must be designed for the maximum storm wave expected for the specified recurrence interval. The methods and analytical procedure's appropriate for wave force determination"are highly structure dependent and vary in design importance among the many feasible concepts appropriate for the water depth range of the study region.

Closed-form solutions do not exist for the calculation of wave forces on unusually shaped, large volume structures. Digital computers are extensively utilized in state-of-the-art numerical solutions for boundary value problems in modified potential flow theory, more commonly called diffraction theory. The procedure often requires a time stepped solution for the velocity potential of the flow around the structure, obtained at any one instant in time by integral equation methods generally based on Green's theorem. The intended result of such a three-dimensional sink-source analysis for an offshore structure is to obtain:

- total linear dynamic wave excitation forces and moments,
- linear dynamic pressure distribution over the surface of the structure,
- added mass and damping coefficients of the structure,
- mean non-linear horizontal wave drift forces and moments, and
- linear dynamic motions in six degrees of freedom for the structure.

The wave forces on the various structures proposed in this study have been estimated based on “previously published results of model testing and theoretical analyses conducted primarily for existing North Sea loading and storage, gravity-type structures. In calculating wave forces based on analyses of existing structures, due consideration was given to the effects of the following parameter variations:

- water depth,
- wave height, period, and length,
- structure shape, dimensions, and volume,
- structure characteristic dimension/wave length relationship, and
- wave height/water depth relationship.

References by Isaacson and Wu (1984), Croasdale and Marcellus (1978), Swift and Dixon (1983), Apelt and Macknight (1976), Garrison et al. (1974), Hogben and Standing (1974), Isaacson (1981), Kokkinowrachos and Wilckins (1974), Loken and Olsen (1976), Skjelbreia (1979), and Torum et al. (1974) were used in determining wave effects and forces on large, rigid structures.

### 3.2.3 Wind Forces

Wind forces on all offshore facilities have been determined in accordance with API RP2A "Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms" (1982).

### 3.2.4 Current Forces

Current forces on all offshore facilities have been determined in accordance with API RP2A (1982).

### 3.2.5 Seismic Forces

Seismic responses for all offshore facilities have been determined in accordance with API RP2A (1982). The seismic analysis for each structure has been performed only to the point of insuring concept feasibility and global stability on the assumption that detailed results will not significantly affect the cost of the various platform concepts and final conclusions of the study.

## 3.3 PETROLEUM PRODUCTION PARAMETERS

Primary production from the study area will be crude oil. It is assumed that the production of non-associated gas from Beaufort Sea fields in water depths greater than 20 m (65 ft) will not be economically justified for at least 20 years. There are estimated onshore gas reserves in the Prudhoe Bay area sufficient to fully utilize a trans-Alaska gas pipeline for at least 20 years thus precluding the possibility of developing offshore gas resources for at least that period of time.

It is assumed that sufficient quantities of associated gas will be available for fuel. Excess gas beyond that utilized for fuel will be reinfected.

### 3.3.1 Crude Oil Properties

For purposes of this study, crude oil properties similar to the published properties of Prudhoe Bay crude oil (Thompson et al., 1971) are assumed. The assumed properties are as follows:

| | |
|---|---|
| -Gravity, specific | 0.893 |
| -Gravity, API | 27.0 |
| -Pour Point, °C (°F) | -9 (15) |
| -Viscosity, Saybolt Universal | |
| @ 25°C (77°F) | 111 sec. |
| @ 38°C (100°F) | 84 sec. |

| | |
|---|---|
| -Gas/Oil Ratio, $ft^3/B$ | 750 |
| -Water/Oil Ratio | Not to exceed 30% |
| -Organic Sulfur, % | 0.2 |
| -Wellhead Temperature, °C (°F) | 80 (176) |

### 3.3.2 Production Characteristics

Production characteristics have been derived from previous work by the National Petroleum Council (NPC, 1981). Production has been idealized as three phase: oil, gas and water, with oil as the primary constituent. As noted above, associated gas will be of sufficient quantities to provide fuel with excess quantities to be reinfected. Produced-water will be separated, cleaned and reinfected. Special production problems such as "heavy crude or high pour point, sour gas ($H_2S$), $C0_2$ and oil/water emulsions have not been included. Reservoir pressure has been assumed sufficient to maintain designed production rates without pumping. Reinfection of associated gas and water injection will be the only pressure maintenance required. The ratio of producing wells to injection wells has been taken as 3:1. It is important to recognize that the many factors which determine the commerciality of a given field, such as, recoverable reserves, depth of wells, hydrocarbon gravity, bottom hole pressure, etc., can vary widely. Any one or a combination of these factors could adversely affect the economic feasibility of a given field.

Well productivity and reservoir depth and configuration control the production rate that can be achieved from a single platform. Production characteristics developed by NPC (1981) indicate a well maximum flow rate of 4,000 BPD and this assumption has been adopted for this technology assessment. It has been further assumed that reservoir characteristics will be such that approximately 68 well slots (including production and injection wells) on a single production structure can be utilized to produce 200,000 BPD.

The following reservoir performance has been assumed:

- peak annual rate of 9.1 percent of initial reserves,
- building up of peak rate from production startup is 20 percent per year,
- peak rate occurs in years six, seven, and eight,
- starting in year nine, decline is exponential at 12 percent per year, and
- production ceases at the end of year twenty.

Production facilities will be assumed similar to those stipulated in the NPC Arctic Oil & Gas Report (NPC, 1981), namely:

- Oil and gas separation
- Oil dehydration and shipping
- Gas dehydration and compression for reinjection
- Water flood
- Drilling rigs
- Utilities and power generation
- Safety and fire protection systems
- Quarters
- Cranes, heliports and escape capsules
- Supply storage areas

## 3.4 SAND AND GRAVEL RESOURCES

Adequate sources of granular borrow material are required for offshore development, but the quantity and quality required for any particular development concept may vary widely. Aside from requirements for artificial island construction (generally in water depths shallower than those considered here), sand and gravel are required for a number of exploration and production platform concepts, as well as development-related offshore-onshore facilities (e. g., pipelines, causeways, etc.). Suitable aggregate is also needed for concrete production.

Potential sources of onshore and offshore borrow are shown in Figure 3.4-1 and described below. Estimates of potentially available quantities and likely material quality are provided. Also, methods available for extraction and utilization of borrow materials are discussed.

### 3.4.1 Borrow Source Locations

As shown on Figure 3.4-1, both onshore and offshore sources are identified; the distribution and characteristics of the latter are less well known. In all instances, site-specific field and laboratory studies are required to prove up these resources. Available information is summarized below.

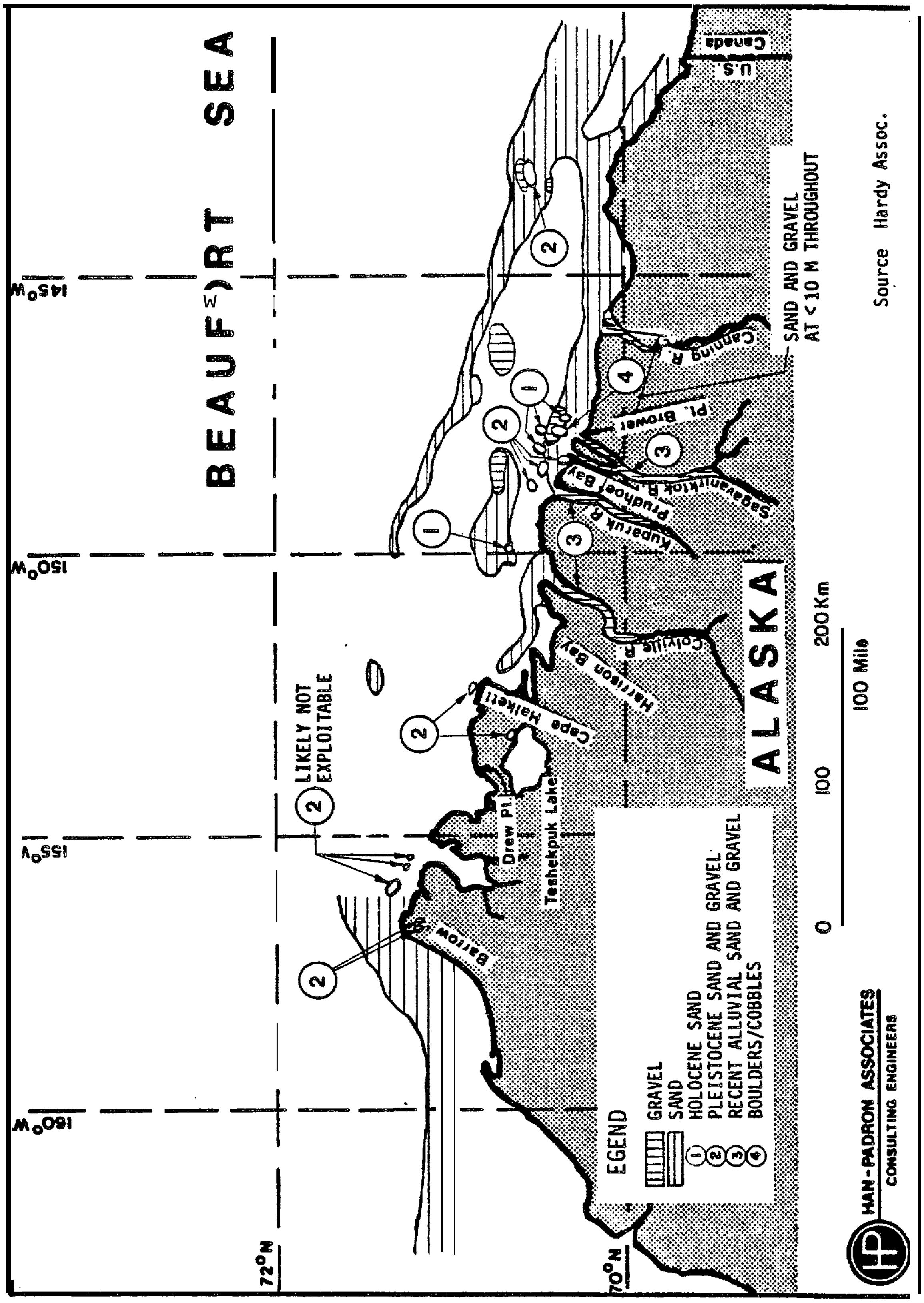

**Figure** 3.4-1. Onshore and offshore borrow locations.

### a) Onshore Sand and Gravel Deposits

Onshore granular borrow potential is greatest in areas to the east of the Colville River. Four main types of sources are identified as follows:

1) Pleistocene Sand and Gravel - A thick deposit of Pleistocene sand and gravel is extensively developed in the subsurface on the Arctic Coastal Plain east of the Colville River. This material occurs beneath up to 10 m (33 ft) of more recent silts, clays and organics, and is continuous with the offshore deposit described below. One constraint on development of these deposits is the occurrence of permafrost at shallow depth on the Arctic Coastal Plain. Deepening of thermokarst lakes that may have an existing "thaw bulb" beneath them is suggested as an alternative means of development (Hopkins, 1978).

2) Ridges and Mounds - According to Hopkins (1978), sand and gravel exist in the Barrow area, in a series of ridges and mounds that form part of an old barrier island chain. Central Marsh Ridge is an example of this type of source. LaBelle (1973) indicates that a gravel deposit exists near the

western shore of Teshekpuk Lake. Otherwise, the lakes on the Arctic coastal plain are devoid of granular material.

3) River Beds - Inactive portions of the braided floodplains and deltas of such high energy rivers as the Colville, Kuparuk, Sagavnirktok and Canning have traditionally served as a prime source of granular material for onshore development activity (and artificial island construction). These sources generally contain good quality granular borrow (gravel and course sand). Rivers within the Arctic Wildlife Range have not been exploited for borrow material. Those in the western section (west of the Colville) are low energy streams, in general, with little potential for coarse granular borrow.

4) Coastal Beaches - Coastal beaches between Cape - Halkett and Drew Point consist of gravel and coarse sand. As a result, some potential may exist for their use as a source of borrow material. Other beaches are apparently either poorly developed and narrow, or comprised of fine-grained material only. Borrow from coastal beaches, or from any other source, within the National Petroleum Reserve -

Alaska (NPRA) may not be used for any development outside of the area.

b) Offshore Sand and Gravel Deposits

Four main types of offshore sand and gravel sources are identified. These are as follows:

1) Holocene Seabed Sediments - Recent (Holocene) sand (and locally available gravel) deposits have developed offshore, primarily through reworking of Flaxman Formation sediments (forming lag deposits) as well as erosion of coastal bluffs. The inferred (and generalized) distribution of such deposits, located primarily west of Cape Barrow and to the east of Cape Halkett and the Colville River, which are 1 to 2 m (3 to 6 ft) thick, is shown on Figure 3.4-1. In the absence of site-specific data, their occurrence is difficult to determine in detail.

2) Pleistocene Sands and Gravels - A widespread granular deposit of Pleistocene age, well suited for use as borrow, occurs in the subsurface, apparently from the Colville River eastward to the Alaskan-Canadian boundary. It is generally overlain by more recent sediments, of the Flaxman

Formation (overconsolidated silt) as well as fine-grained Holocene materials. Again, the suitability of these deposits for exploitation as a borrow source must be determined on a site-specific basis, since wide variations exist in the thickness and characteristics of the overlying deposits. Existing data suggest that relatively shallow overburden exists close to Prudhoe Bay. However, the Pleistocene deposits become increasingly sandy and silty (and less gravelly) seaward, while the overburden deposits become thicker, and the Flaxman Formation silts more prevalent towards the east (Hopkins, 1978).

3) Barrier Islands - These are a traditional source of granular borrow (primarily gravel). Recent studies, however, indicate that many are "relict" features that once destroyed will not be rebuilt by present-day geologic processes. The State of Alaska now prohibits gravel extraction from the barrier islands and nearshore areas where it is demonstrated that extraction of gravel will adversely affect the environment.

4) Cobbles and Boulders - A large accumulation of boulders (referred to as a boulder patch) occurs on

the seabed in Stefesson Sound between Point Brewer and Narwhal Island but, due to its environmental significance, this material will not be available for borrow.

### c) Priorities For Borrow Source Development

Past experience, increasing knowledge of geologic processes on the Arctic coastal plain and adjacent continental shelf, and a recognition of environmental concerns have led to an awareness of the possible impacts of sand and gravel extraction. Lease restrictions and implementing regulations will also be a factor in borrow source development. Scientists and industry have assessed the various possible borrow source types for development, in order of decreasing preference, as follows:

1) Abandoned artificial islands and causeways. This practice (recycling) has already been adopted in the southern Canadian Beaufort Sea. However, it should be recognized that there are several major problems with using abandoned artificial islands and causeways as a reliable gravel resource. These islands could become habitats for birds and/or wildlife. Also, the core of artificial islands and causeways will likely be frozen and more difficult to recycle and it may not be economical to reuse

such a small resource, particularly when the resource is not in the proximity of a new development.

2) Terrestrial mining, by means of open pits. The Pleistocene sand and gravel deposits that exist at shallow depth beneath the eastern part of the coastal plain are the preferred onshore borrow source, from the environmental point of view. Wherever feasible, pits should be located at least 1 km (0.6 mi) from the coast to avoid cultural sites.

3) Sea bottom outside the 5 m (16 ft) bathymetric contour. The seabottom Holocene sands and buried Pleistocene sands and gravels, are the preferred offshore sources, from the environmental standpoint. According to Hopkins, these offshore deposits may be developed, by dredging, with only limited environmental impact, related primarily to increased turbidity. In deeper water, natural processes will probably infill dredged depressions within a relatively short time.

4) River beds. Pit development in river floodplains, as well as in marshes and wet lands, is undesirable, since channels and fish habitat may be disturbed. Mining site development and rehabilitation within floodplains must follow the procedures outlined in <u>Gravel Removal Guidelines For Arctic And Subarctic Floodplains,</u> 1980, U.S. Fish and Wildlife Service.

5) Beaches and sea bottom inside the 5 m (16 ft) bathymetric contour. Dredging in nearshore lagoons is not recommended. The boulder patch, offshore from Narwhal Island, is identified as environmentally sensitive and will not be available for development.

6) Barrier island system. Offshore barrier islands are considered to be relict landforms that, once disturbed, would not be replaced by natural processes. So even though they may contain attractive large volume gravel sources, State regulations prohibit mining.

### 3.4.2 Quantity and Quality

#### a) Available Quantities

Few data are publicly available regarding likely quantities of material available in the various onshore sources, and detailed information on the offshore deposits is lacking. Some proprietary information exists but has not yet been made publicly available.

Information on onshore sources, mainly after LaBelle (1973), may be summarized as follows:

1) In the area of Barrow, coarse sand and gravel resources in pits, barrier islands, beaches, etc., are estimated in the order of $19\times10^6$ $m^3$ ($25\times10^6$ $yd^3$). Of this quantity, only $3\times10^6$ $m^3$ ($4\times10^6$ $yd^3$) may be exploitable.

2) Some 700,000 $m^3$ (900,000 $yd^3$) are estimated to be present northwest of Teshekpuk Lake.

3) The Colville River, south of its delta (predominantly silt and fine sand), contains an estimated $27\times10^6$ $m^3$ ($35\times10^6$ $yd^3$) of sand and gravel.

4) The river beds east of the Colville are not well

investigated. However, those of the Kuparuk and Sagavanirktok have been extensively exploited in connection with development at Prudhoe Bay.

5) Buried Pleistocene sands and gravel are widespread between the Kuparuk and Canning River. Open pits or deepening of thaw ponds may permit these resources to be developed.

Two main offshore sources of interest are Holocene muddy sands and lag gravels and buried Pleistocene sands and gravels. The former deposits are expected to be between 1 to 2 m (3 to 6 ft) thick and discontinuously distributed. Available volumes at any one location may be small. The Pleistocene deposits, though buried, are extensive and-apparently in excess of 10 m (33 ft) thick. This material constitutes the largest, easily extracted, source of good quality aggregate on the Alaskan Shelf. Site-specific studies are required to prove up these deposits prior to development.

b) <u>Aggregate Quality</u>

Existing information is not adequate to provide more than a general assessment of granular material quality in the various onshore and offshore sources. For this reason, site-specific field testing of identified sources will be required prior to development. The following generalizations may be made:

1) The Pleistocene sands and gravels that occur in the subsurface of both the Arctic Coastal Plain and Shelf are expected to be well suited for use as granular fill.

2) River bed deposits and, where exploitation is feasible, barrier island sources are also expected to be of good quality.

3) The onshore mound and ridge deposits and sources close to Teshekpuk Lake are anticipated to be of fair to good quality.

4) The offshore Holocene muddy sands and coastal beach deposits may be of variable composition and sporadically distributed, It is expected these deposits may be less well suited to development as granular borrow sources.

5) No data are available upon which to base an assessment of aggregate suitability for use in concrete. However, Rodeick (1974) indicates that some surface gravels on the shelf consist predominantly of black chert (of interior Alaska origin). Previous experience with chert suggests

this material may not be well suited for use in concrete.

## 4.0 TECHNOLOGY AND COST EVALUATION BASIS

This chapter describes the technology, manpower requirements, capital costs and operating costs of petroleum development activities that are related to a number of different exploration, production and/or transportation concepts. Thus, it serves to define the "building blocks" used to develop the technology assessment of offshore Arctic petroleum exploration, production and transportation that are described in the following three chapters.

## 4.1 ARCTIC CONSTRUCTION TECHNIQUES, MANPOWER REQUIREMENTS AND COSTS

The construction techniques unique to offshore construction in the Beaufort Sea, along with relevant unit costs, are presented below. The categories considered include: sand and gravel extraction and utilization, dredges and dredging, towing large offshore structures, and structure concept and prefabrication techniques.

### 4.1.1 Sand and Gravel Extraction and Utilization

#### a) Onshore Extraction Methods

To date, the borrow sources for all islands constructed in the Alaskan Beaufort Sea have been onshore gravel pits. There are several known onshore borrow sources as discussed in Section 3.4. With the possible exception of pits developed within river channels (development of which may be environmentally unacceptable), onshore borrow sources consist mainly of frozen material in relatively deep pockets. Two possible approaches to extraction and utilization have commonly been adopted:

1) Sand and gravel may be extracted, by ripping and/or blasting, and utilized for construction in the frozen condition. Thaw settlement and densification of placed fill upon thawing may be anticipated.

2) Granular material may be extracted in the unfrozen condition by excavating it each summer as active layer development (thawing) proceeds. The sand and gravel may be used immediately or stockpiled for winter construction. However, on the Alaskan North Slope the daily thaw rates and very limited summer thaw season have not favored this approach.

Dredging of (unfrozen) Pleistocene sands and gravel beneath lakes on the Arctic Coastal Plain has been proposed by Hopkins (1978) as an alternative, environmentally attractive approach.

Onshore borrow material could be used most economically for offshore construction of shallow water islands in less than a 12 m (40 ft) water depth. To date, several islands have been built in this manner with the materials being trucked to the location over ice roads.

For the deeper water islands or berms this method is not safe, since the ice, although land fast, is constantly moving and unexpected leads in the ice will render ice roads useless. Also, ice in deeper waters is usually very rafted and inaccessible by conventional trucks. If the use of onshore gravel is considered for the deeper water islands, the material should be stockpiled offshore on barrier islands where it can easily be recovered by floating equipment in the open water season and loaded on barges for further transportation.

b) Offshore Extraction Methods

No dredging associated with the construction of exploration platforms has yet taken place in the Alaskan Beaufort Sea. Therefore, difficulties and costs associated with permitting requirements are somewhat uncertain.

The selection of an economical borrow source depends primarily on:

- haul distance to the site,
- type of material, and
- depth of borrow site.

Coarser material results in better foundation conditions and shorter construction periods than finer materials. Gravel allows steep slopes of 1:3 to 1:5, while with sand, slopes may be as flat as 1:10 to 1:15, which would require much greater volumes. The stability and erosion resistance is also better for gravel than for sand, the latter, if very fine, being subject to liquefaction under storm wave and earthquake conditions.

Shallow water depths can restrict the draft of dredging equipment and make a site less attractive as a source of borrow material. In a contrary fashion, the depth may be great, which will require special dredging equipment.

The packing, or in-situ density, of the material also affects its desirability as a borrow source. Denser material will require more power to excavate and will result in lower production rates than loose materials.

As discussed previously, there are two principal known types of borrow sources offshore Alaska:

- Sand/gravel deposits which are covered with a 2.5 to 9.0 m (8 to 30 ft) layer of clay and silt.
- Fine to medium sand deposits in layers of 1.0 to 6.0 m (3 to 20 ft), not covered with overburden.

The techniques utilized to exploit each type of deposit are different and are described separately below. Costs for dredging sand and gravel deposits are given in Section 4.1.2.

### 1. Sand/Gravel Deposits

Excavation and transportation of sand/gravel deposits overlain with clay is feasible by pumping directly to the site or by loading into hoppers for transportation to the site.

Pumping directly to site

If the material is not too densely packed, it can be excavated with a stationary dredge equipped with water jets as shown schematically in Figure 4.1-1. The dredge will first jet a hole through the clay and begin to dredge sand from beneath the clay layer. The clay will be undermined and will eventually slough down in big lumps remaining on the bottom of the created pit. Small amounts of clay will be entrained in the pumped mixture, either in the form of clayballs or as suspended particles in the slurry-like mixture. The mixture will be pumped through a floating pipeline and settle at the island site. The clay lumps will form part of the island fill but will not influence the stability of the island foundation as long as the clay percentage is less than 5 to 15 percent of the total fill volume. The clay in suspension will be washed away by the current and will settle mainly outside the construction area.

The production capability of such a dredge depends primarily on the face height of the sand and the layer thickness of the overburden. Typical production rates, based on a pipeline diameter of 30 to 32 in., are as follows:

- Overburden 0 to 1.5 m (0 to 5 ft) and sandface 15 m (50 ft): production 3,000 to 3,800 $m^3$/hr (4,000 to 5,000yd$^3$/hr)

- Overburden 1.5 to 4.5 m (5 to 15 ft) and sandface 15 m (50 ft): production 2,300 to 2,700 $m^3$/hr (3,000 to 3,500yd$^3$/hr)

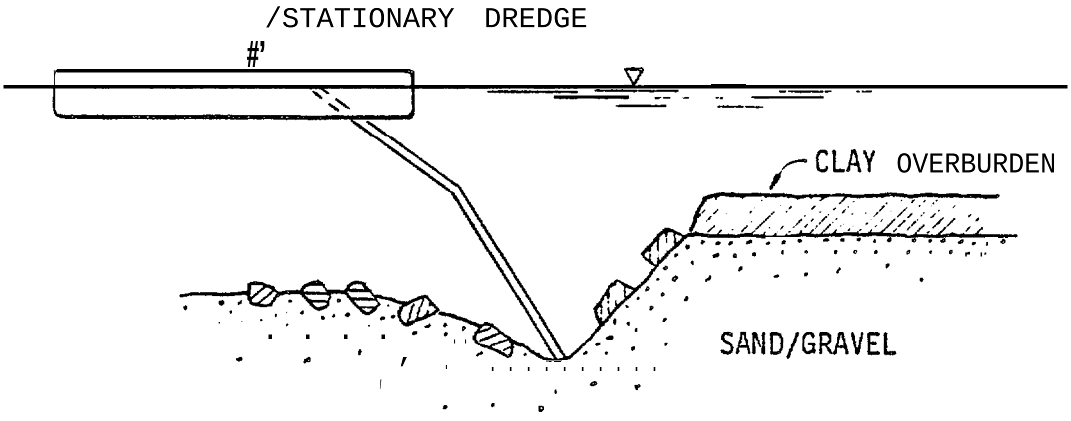

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Figure 4.1-1. Excavation of sand/gravel deposits with clay overburden.

- Overburden 4.5 to 9.0 m (15 to 30 ft) and sandface 15 m (50 ft): production 1,500 to 2,300 $m^3$/hr (2,000 to 3,000 $yd^3$/hr)

- Overburden 4.5 to 9.0 m (15 to 30 ft) and sandface 9 m (30 ft): production 1,100 to 1,500 $m^3$/hr (1,500 to 2,000 $yd^3$/hr)

In the last case, the production rate for the stationary dredge drops considerably and a cutter suction dredge would be a better solution. Also, a cutter dredge would be used when the material is very dense (in-situ specific gravity over approximately 2.1). This type of dredge would strip and dispose of the overburden before excavating the sand or gravel. The average production rate would normally be in the range of 1,100 to 1,500 $m^3$/hr (1,500 to 2,000 $yd^3$/hr). The actual production rate of the cutter dredge will depend mainly on the installed power and could be as high as 1,900 $m^3$/hr (2,500 $yd^3$/hr).

In the event that gravel is excavated, another delineating factor in the production rate will be the discharge pipeline resistance. The slurry mixture will be pumped with a speed of 5.5 to 6.0 m/see (18 to 20 fps) with not more than 10 to 12 percent of entrained material, therefore, the pipeline diameter and installed power in the pumps will determine the production rate.

For a further discussion of dredging operations refer to Section 4.1.2.

Loading into hoppers

Loading the dredged material into hopper barges is essentially the same process as the direct pumping method except that the finer parts in the dredged mixture will not remain in the barge but will be removed with the hopper overflow. Since the discharge length of the pipeline is short, its diameter will have less of an influence on the production rate than for the direct pumping method.

In the case of a cutter dredge, a short piece of pipeline connects the dredge with a barge loading pontoon. The cutter dredge sweeps from port to starboard pivoting around a stern spud. The hopper barges are moored clear of the dredge so as not to restrict this movement.

### 2. Fine to Medium Sand Deposits

Fine to medium sand deposits in layers of 1.0 to 6.0 m (3 to 20 ft) are only marginally economic sources for excavation with a cutter dredge because the production rate is substantially lowered by the constant relocating operations for the spuds and anchors.

A stationary dredge could only operate in such a thin layer if it is equipped with a "dustpan" type of suction mouth. The production rate with this equipment will also be relatively low.

A trailer suction hopper dredge is most suitable for excavating this type of borrow source providing the dimensions of the deposit are at least 5 to 10 times the length of the dredge.

Sand with a mean grain size ($D_{50}$) less than 200 microns is not suitable for island fill material. Material with a mean grain size between 150 and 200 microns can be used as ballast material for caissons. Material finer than 150 microns will be difficult to load into barges or hoppers because most of the material will be discharged with the hopper overflow.

For a further discussion of dredging operations refer to Section 4.1.2.

### c) Island Construction Techniques

For the construction of artificial islands utilizing offshore dredged fills, the compaction requirements depend on the side slope and the method of placing the sand or silty sand. Based on dredging experience, it is unwise to design islands with steeper than 10 horizontal to 1 vertical side slopes unless special construction techniques are employed to place and compact the sand. It is recommended that dredged sand be placed by bottom barge dumping as the momentum from the slug of sand dropping through the water and impacting on the seabed improves the compaction. Various techniques used to tremie sand into place at steep side slopes (about 5 horizontal to 1 vertical) have resulted in low sand densities and a loose sand structure. Sand in such a condition is only metastable and is subject to liquefaction induced by either exterior forces or localized overstressing.

Various compaction procedures have been proposed for submarine sand. Vibroflotation has been suggested for Canadian Beaufort Sea Islands but has never been used. This process liquefies the sand locally and therefore cannot be used adjacent to slopes steeper than about 15 horizontal to 1 vertical. Recently a sparker system has been tank tested to improve the density of sand placed by tremie procedures but it has not been field tested. The sparker system is an adaptation of the sparkers used in the offshore geophysical industry as an energy source for seismic surveys.

If islands are to be built with side slopes in the order of 12 or 15 horizontal to 1 vertical using dredged fine sands and bottom dumping techniques, no compaction procedures need to be considered. - If side slopes in the order of 5 horizontal to 1 vertical are proposed, it is imperative that the density be increased by compaction to above a critical relative density of approximately 50 percent. This precise value must be determined by laboratory testing. The density of the sand must be above the critical point and must be such that the sample dilates under shearing stress. If the reverse happens and the sample reduces volume or collapses under shear stress then the sand mass is metastable. Consequently, if innovative techniques are used to place the submarine sand at steep angles, these techniques must be combined with some form of compaction to insure that the relative density is above the critical value. Sand which is placed by spilling from the end of a floating pipeline will naturally take up a side slope of about 12 horizontal to 1 vertical and therefore compaction is not required because of the low stress level in the sand.

For artificial island construction used to date in the Canadian Beaufort, the fill material has either been pumped directly into the island site or dumped from barges and/or trailer hopper dredges. In the latter case the dumping height is restricted to 0.6 to 1.0 m (2 to 3 ft) below the draft of the equipment. Sand fill required on a higher level is either dumped in a stockpile and re-handled with a cutter/stationary dredge or pumped out of the hopper. A berm is formed just above water level and, as soon as dry land surfaces, bulldozers and backhoes are mobilized to build a retaining bund around the island with a weirbox. Erosion protection is-immediately placed on the beach around the bund. Once the bund is completely closed, the area is filled with sand or gravel to a level of 2.5 to 3.0 m (8 to 10 ft) above water level. When this is finished, a second bund is placed and again the area is filled, now to a level of about 6 m (20 ft) above water level. The floating pipeline is extended with a shore based pipeline to accomplish this end.

Although dredged sand and silty sand fills have been used extensively in the Canadian Beau fort Sea, experience in the Alaskan Beaufort Sea has centered around the use of onshore gravel borrow, trucked across the ice and dumped through the ice. In these cases, where the mean grain size ($D_{50}$) is in the range of 10 mm, gravel islands can be constructed at side slopes of about 3 horizontal to 1 vertical (Agerton, 1983; Tart and Colonell , 1984). No particular efforts have been taken to compact the gravel, other than the normal passage of construction traffic when the gravel core was elevated above sea level.

### 4.1.2 Dredges and Dredging

This section addresses the technology and costs associated with dredges and dredging operations in the Beaufort Sea study area. The section is arranged as follows:

a) State of the art and operating limitations of dredging equipment in use in the Canadian Beaufort Sea.

b) Discussion of dredging operations and unit costs in the Alaskan Beaufort Sea.

c) Basis for developing unit costs.

d) Design criteria for future dredges and barges.

e) Dredge wintering requirements.

a) State Of The Art

In 1975 the Canadian oil industry began constructing artificial islands for exploration purposes in the Canadian Beaufort Sea in water depths greater than 7.5 m (25 ft). Previously, several islands had been built in shallower water depths and they served as test cases for the larger islands. To date, artificial islands with a sacrificial beach have been built in water depths of up to 20 m (65 ft). Some berms, to support concrete or steel structures, have been built in water depths of 24 to 40 m (80 to 130 ft). The material that has been used to construct the berms and islands is sand with a mean grain size ($D_{50}$) of 250 to 350 microns. The island beaches are protected with filter cloth and ballasted with 1.5 to 2.0 $m^3$ (2to 2.5 $yd^3$) sandbags.

In general, conventional equipment was used for the construction of the berms and islands with some modifications made to cope with the Arctic environment. With respect to the operational season, the prevailing ice conditions in the Canadian Beaufort Sea are less severe than offshore Alaska. The Canadian operational season normally begins in the middle of July-and continues through the middle of October. However, 1983 ice conditions were particularly bad and operations ceased in the second part of September.

The dredging depth capability of conventional equipment is generally not deeper than 30 m (100 ft). In the Canadian Beaufort Sea the following dredging equipment has been or still is in use to construct artificial islands and berms:

- Cutter suction dredge with underwater and booster pumps

The cutter suction dredge is a dredge in which the suction pipe is provided with a rotating cutting device. The dredge is suitable for dredging all materials present in the study area except frozen materials with a compressive strength in excess of 10,000 kPa (200,000 psf). The excavated material is dredged as a mixture with water and pumped either through a discharge pipeline to a disposal site or into a hopper barge. The dredge usually is equipped with two spuds and a spud carriage system. During operations, the dredge pivots around a spud with the help of side anchors. The cutter head excavates the material in quarter circles, each time moving ahead approximately 1 m (3 or 4 ft) while creating an excavated face 1.5 to 2.5 m (5 to 8 ft) thick. The side anchors must be shifted after the dredge has advanced 30 to 60 m (100 to 200 ft). This can be done by an anchor handling tug or by anchor booms if the dredge is so equipped.

In the Canadian Beaufort a cutter suction dredge was used to dredge a channel and harbor and later used to place the berm for a caisson retained island. The dredge has the following characteristics:

- Discharge pipeline diameter - 32 in.

Installed power - 9,000 hp

Dredging depth - maximum (with cutter) 24 m (80 ft)

Production rate - 1,900 to 4,600 $m^3$ (2,500 to 6,000 $yd^3$) of sand per hr

A cutter suction dredge can work in wave heights up to 1.0 to 1.2m (3 to 4 ft). Many existing dredges are not sufficiently seaworthy to operate far offshore where wave heights of 3 to 4 m (10 to 13 ft) can occur. However, this condition will be a requirement for Beaufort Sea operations. A cutter suction dredge which normally operates with a floating pipeline cannot be operated in an area with drifting ice floes. Only when the ice is drifting very slowly (less than 0.5 knot), will tender-tugs be able to move ice floes less than 300 m (1,000 ft) in diameter out of the way. In new ice formation, operations must cease when the ice thickness is in excess of 0.3 to 0.5 m (1 to 1.5 ft).

- Stationary dredge with underwater and booster pumps

The stationary dredge is only suitable for dredging soft granular materials: sand or gravel with a low silt or clay percentage. The sand is agitated by a water jet system which brings the materials in suspension after which it is lifted by the dredge pumps. During operation, the dredge pipe forms a deep pit and the material sloughs in along the side slopes of this pit towards the suction mouth. The dredge remains stationary during dredging operations and is periodically moved a distance of 2 to 3 m (5 to 10 ft ).

When constructing the artificial island, the dredge was used for material located close to the construction site and pumped directly into the island. The dredge pipe was later provided with a cutting device to dredge cohesive materials. It was also used to dredge holes to a depth of 40 m (130 ft) to accommodate B.O.P. stacks below the seabed. The dredge has the following basic characteristics:

- Discharge pipeline diameter - 32 in.
- Installed power - 7,000 hp
- Dredging depth - maximum 50 m (165 ft)
- Production rate - 1,900 to 4,600 $m^3$ (2,500 to 6,000 $yd^3$) of sand per hr

A stationary dredge equipped with a swell compensating dredge ladder can operate in 2.5 to 3.5 m (8 to 12 ft) waves when used with a floating pipeline. In a barge loading situation, the moored barge will restrict the operation to wave heights of 1.5 to 2.0 m (5 to 6 ft). The limits in ice infested waters are similar to those for a cutter dredge, except in a barge loading situation where it will be somewhat easier to clear the ice with tugs because of the absence of a floating pipeline.

- Trailer Suction Hopper Dredges

In principle, the trailer suction hopper dredge consists of a self propelled hopper dump barge to which one or two suction pipes are attached with suction pumps to dredge granular material which is then deposited in the hopper. When the hopper is loaded, the dredge sails to a dump site where the material is unloaded by the opening of bottom doors. This type of dredge is suitable for sand and gravel. Silt and soft clay can be dredged but it is sometimes difficult to dump these materials. The installation of water jets in the barge can overcome this problem.

Five trailer suction hopper dredges have been or are still in use in the Canadian Beaufort to dredge and transport sand to island sites over a distance of 30 to 140 km (18 to 85 mi). The hopper capacity ranges from 3,800 to 9,200 $m^3$ (5,000 to 12,000 $yd^3$). The materials have either been dumped through bottom doors in the hopper or pumped out through a floating pipeline into a caisson retained *or* sacrificial beach island. The dredges have the following characteristics:

- Installed power - 8,000 to 20,000 hp
- Sailing speed - 13 to 16 knots
- Loading of the hopper takes 1 to 1.5 hr
- Dumping takes 0.25 to 0.5 hr
- Pumping ashore takes 1 to 2 hr

The trailer suction hopper dredge can operate in wave heights of 3 to 4 m (10 to 13 ft). In ice covered waters the maneuverability is sufficient to sail around ice floes while dredging. In new ice, operations are feasible in 0.3 to 0.5 m (1 to 1.5 ft) thick ice.

- Five Manitowoc Split-Barges have been used to transport and dump sand material into shallow water islands. These barges are not self propelled and have a transport capacity of 1,500 $m^3$ (2,000 $yd^3$).

### b) Dredging Operations and Costs in the Alaskan Beaufort Sea

The general, site conditions in Alaska are more severe than the conditions at Canadian sites. No operating experience is available for Alaskan Beaufort dredging operations. The study area water depth range is 20 to 90 m (65 to 300 ft) instead of the present maximum depth of 40 m (130 ft) in Canada. The Alaskan summer ice conditions result in an average operational season estimated at 30 to 50 days, depending on the distance from shore, during which island or berm construction can be performed. In any given season, the length of the operational season may vary significantly from the average and may range from 0 to 60 days. The operational season could be extended by developing specially built, ice-capable equipment. However, such equipment could not operate efficiently in closely packed multi-year ice floes and the season would only be extended by 20 to 30 days, during which time the dredging production rate would be considerably lower than in open water.

For most of the envisaged projects in the study area, new equipment must be designed since conventional equipment does not have the required dredging depth capability. Also, as the dredging season will be short, the production capability must be higher than what normally would be considered high. The equipment must be capable of maneuvering in ice covered waters and must, at least, be ice-strengthened. Preferably it should be built to ice class specifications to increase the length of the construction season. All dredges operating in the Alaskan Beaufort Sea must be U.S. built and U.S. registered in conformance with current legislation thus increasing dredging costs compared with Canadian operations. It is anticipated that special dredging techniques will be developed for operation in the deeper water depths.

The types of dredging operations, the several types of dredged materials which can be encountered and dredging unit costs are discussed below.

### 1) Dredging and pumping of material directly into an island, berm or caisson

Dredging and pumping of granular material directly into an island, berm or caisson is only feasible if the materials available at the site are suitable for fill purposes. If suitable materials, such as gravel or medium to coarse sand ($D_{50}$ greater than 200 microns) are present, this is the least expensive and fastest method to fill an island or caisson area or construct a berm. In the event that the sand or gravel is covered with a layer of unsuitable overburden in excess of 1.5 to 3.0 m (5 to 10 ft) thick, this layer would be removed.

Equipment to be employed:

- A stationary dredge when the sand/gravel deposit is over 10 m (30 ft) in thickness, or
- A cutter suction dredge when the layer is thinner.

A conventional stationary dredge can operate to a depth of approximately 50 m (165 ft). A cutter suction dredge can operate to a depth of 27 m (90 ft). It is possible to design and construct dredging equipment which can operate in depths up to 100 m (330 ft). Therefore, if suitable fill materials are present at the site, artificial islands or berms can be built using this method throughout the entire study area. A major disadvantage of this method is that ice floes impacting the floating pipeline can easily interrupt construction operations and a constant ice watch must be maintained. For a more detailed discussion of the extraction and utilization of sand and gravel, refer to Section 4.1.1.

The unit costs of dredging and pumping of sand and gravel directly into an island, berm or caisson are given in Figure 4.1-2 as a function of water depth. The unit costs in the figure are based on in-place quantities of material and allow for losses and consolidation. They are also based on the use of a stationary dredge.

### 2) Dredging transport material for an island, berm or caisson

When sand and gravel material is not available at the site, it must be transported from a borrow source. In general, the material can be transported in an independent unit (self-propelled or towed barge) or in a trailer suction hopper dredge. When transporting by barge, loading can either be done by a stationary dredge or a cutter suction dredge. In the first case, the barges are loaded directly alongside the dredge. In the case of a cutter suction dredge it becomes difficult to moor the barges alongside the dredge because of the constant dredge movement. Therefore, a cutter suction dredge will have a loading pontoon with a

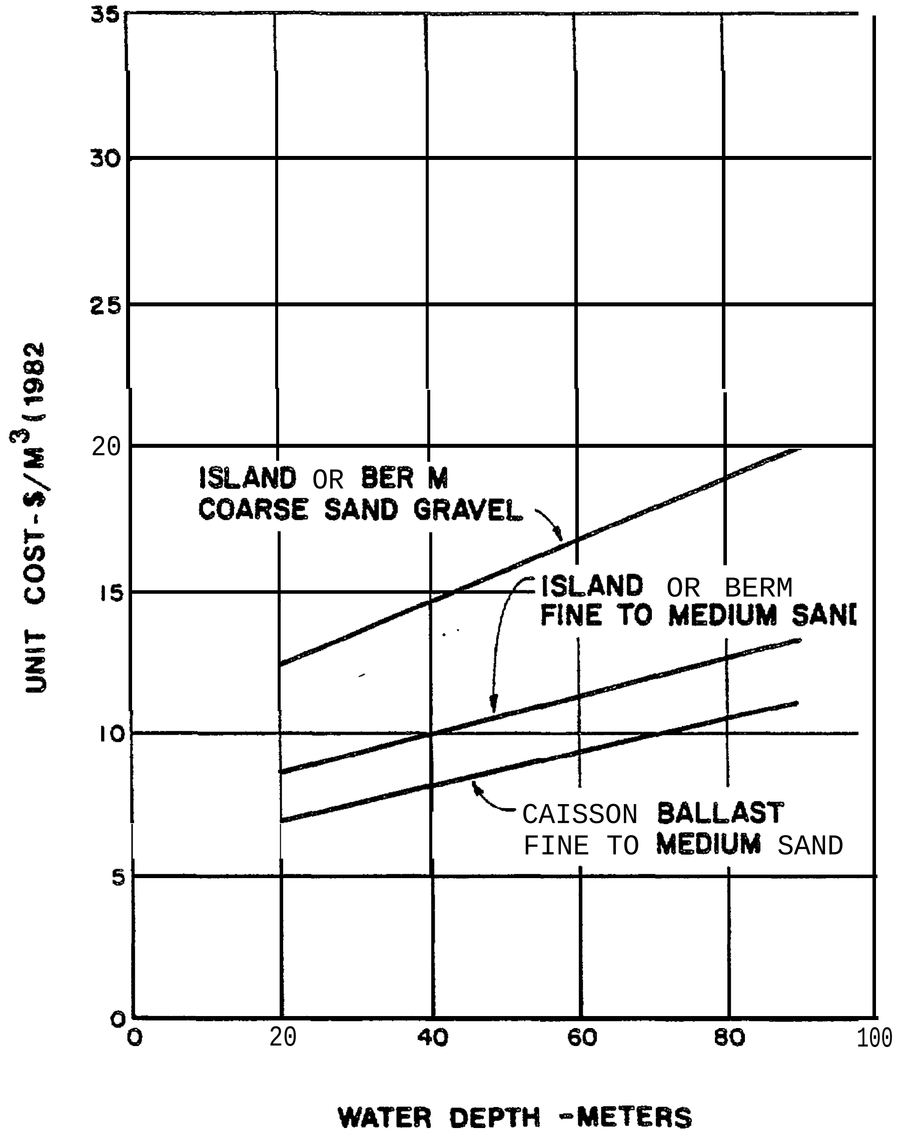

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**Figure** 4.1-2. Unit cost of dredging and pumping **material** directly into island, berm or caisson versus water **depth**.

floating pipeline connected to it to load the barges. Either self-propelled barges or towed barges can be used. The speed and maneuverability of self-propelled barges is much better than towed barges. However, the capital and operating costs of towed barges are lower. Material will be dumped on the island site through bottom doors in the barges or through the use of split-barges. Fog and ice floes will slow down barge operations. With up to 2 okta ice coverage, reasonable sailing speeds can be maintained. In 3 to 4 okta ice coverage the speed will drop to less than 6 km/hr (3 knots) and in 5 to 6 okta coverage the speed will be very slow.

In order to utilize a trailer suction hopper dredge, the borrow area must have sufficient dimensions to allow efficient operation of the dredge. The minimum width of such an area is 450 to 600 m (1,500 to 2,000 ft) and the length should preferably be longer than 1,200 to 1,500 m (4,000 to 5,000 ft). The dredge loads its hopper with two drag-arms while traveling at a speed of 4 to 12 km/hr (2 to 6 knots). Any sand/gravel layer with a thickness in excess of 1.5 m (5 ft) is suitable. In the event that the sand layer is covered with overburden, the trailer suction hopper dredge will strip this layer first. The sailing speed of a trailer suction hopper dredge is 25 to 30 km/hr (13 to 16 knots) in ice free waters. The speed will decrease in the presence of ice floes. The dredged material will either be dumped at the island site or pumped out through a floating pipeline in the event that the material requires placement in a caisson or above the draft level of the vessel. For a more detailed discussion of the dredging and transporting of sand and gravel, refer to Section 4.1.1.

When a caisson is designed to contain sand or gravel ballast to withstand ice forces, it is necessary to place this ballast as soon as possible after set-down of the structure to reduce the risk of damage by invading ice floes. When ballast material haul distance is great, it may be preferable to stockpile the ballast material in advance, close to the site, and re-handle it with dredging equipment after the caisson is set down.

The unit costs of dredging and transporting sand and gravel for an island, berm or caisson are given in Figure 4.1-3 as a function of haul distance, The unit rates have been calculated on the basis of a water depth of 45 m (150 ft) at the borrow site. Correction factors for other water depths at the borrow site are given in the figure. The unit costs are based on in-place quantities of material and allow for losses and consolidation. It has been assumed that the borrow site is suitable for use of a stationary dredge and transportation of the material is by self-propelled barges.

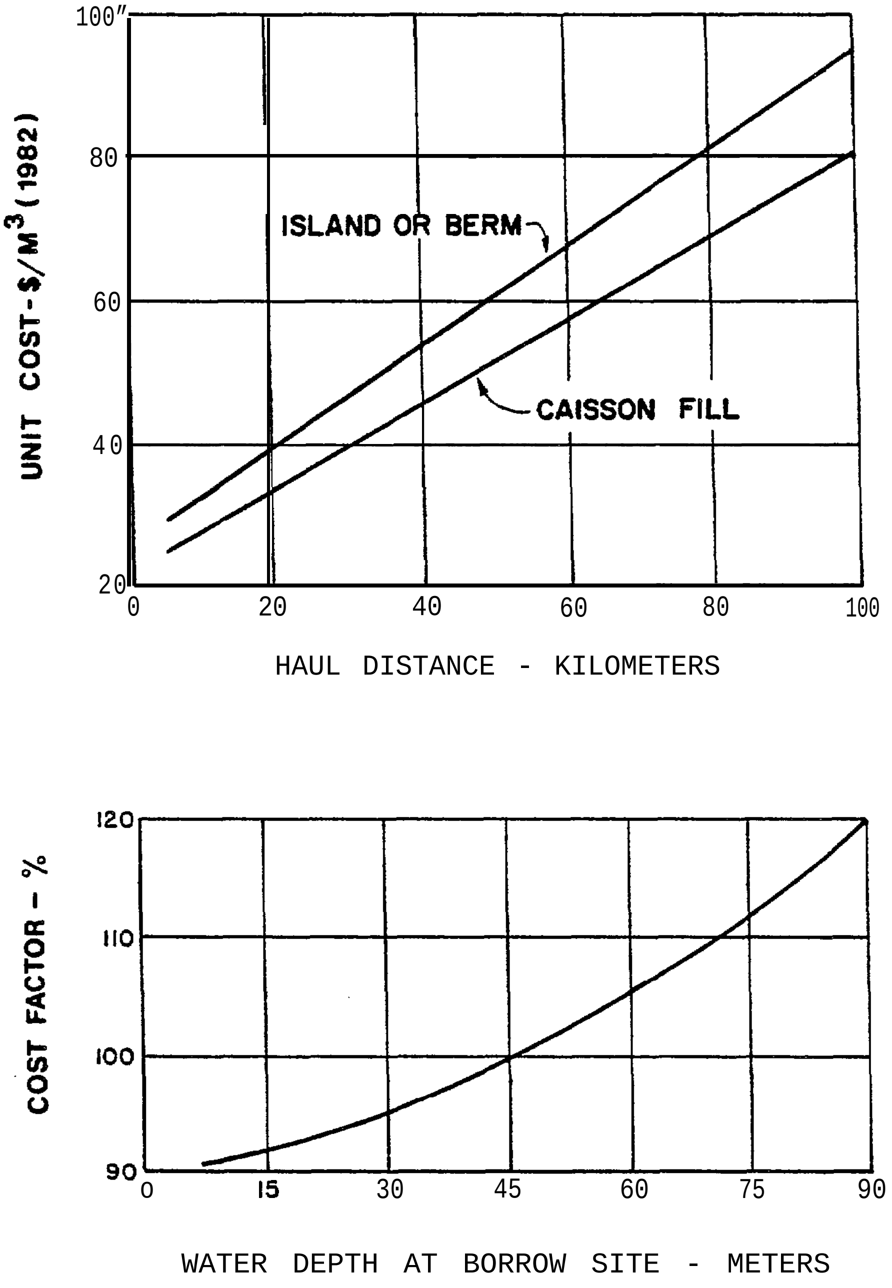

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Figure 4.1-3. Unit cost of dredging and transporting material for an island, berm or caisson versus haul distance.

Since transportation cost is the major portion of the in-place cost and the lower loss factor of coarse material tends to offset the higher cost of dredging this material, a single curve is given in Figure 4.1-3 representing the average unit cost of dredging both fine and coarse granular material. The lower cost of filling a caisson shown in the figure reflects the reduced percentage of material losses for this operation.

3) Stripping of unsuitable materials

Stripping of the seabed will be required when a borrow site is covered with unsuitable materials or when unsuitable materials must be removed to improve the foundation conditions for large platform structures. Conventional cutter suction dredges and trailer suction hopper dredges have a maximum operating depth of 30 to 45 m (100 to 150 ft). In the event that unsuitable materials must be stripped for platform sites in water depths in excess of 45 m (150 ft), special equipment must be designed. A stationary dredge normally is not suitable for this purpose.

Unit costs for stripping unsuitable materials are given in Figure 4.1-4. The costs are based on the use of a cutter suction dredge and are presented for in-situ volumes prior to dredging.

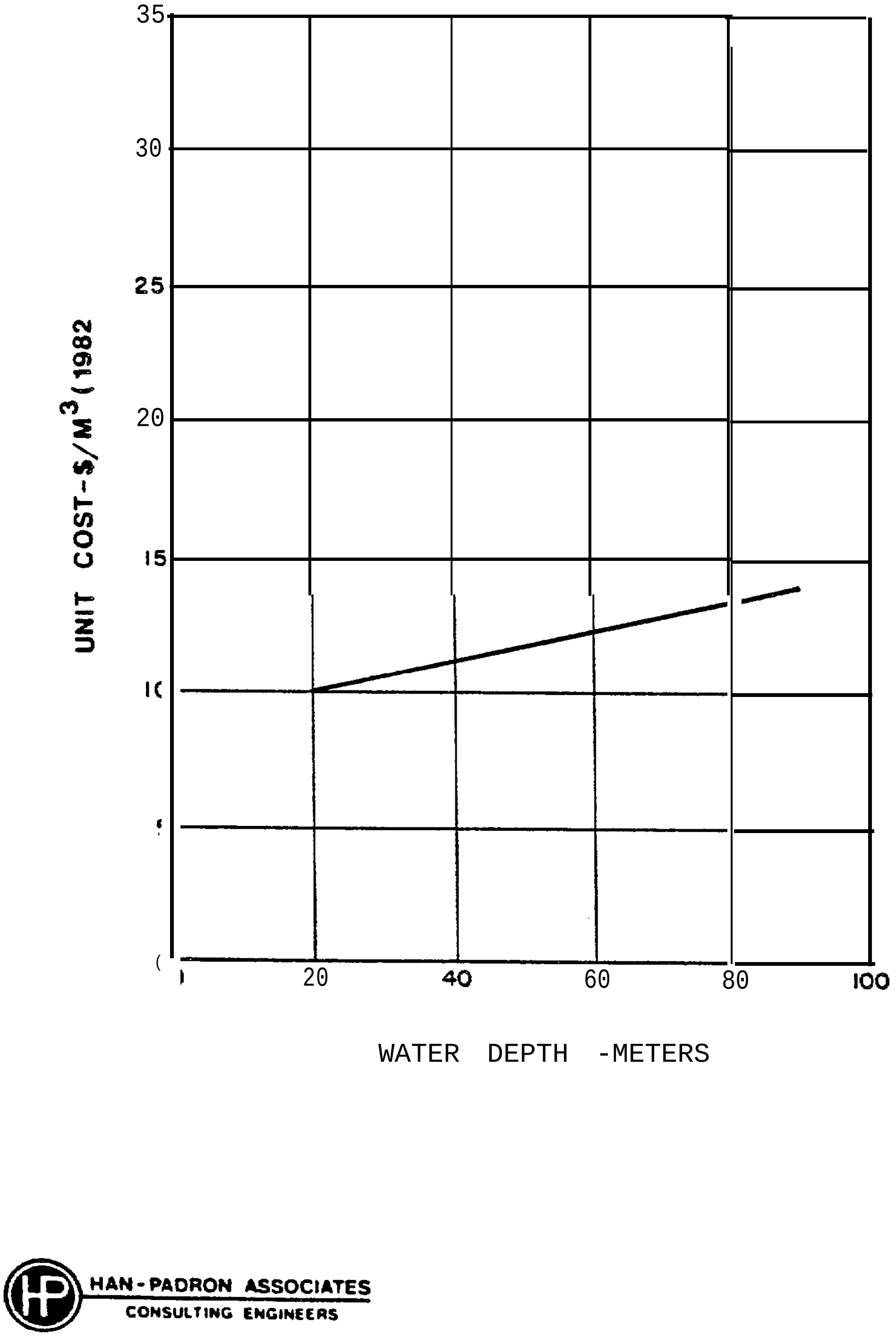

Figure **4.1-4.** Unit cost of stripping unsuitable material versus water depth.

4) Dredging of "Glory Holes"

"Glory Holes" are excavations in the seabed, about 15 m (50 ft) deep, with bottom dimensions of approximately 10 x 10 m (33 x 33 ft) and side slopes of 1 vertical to 3 or 4 horizontal. These excavated pits are used to place blow-out preventers below the seabed, clear of any scouring ice floes. The materials to be dredged can be any material present in the study area. The required equipment must be specially designed since the depth capacity of a conventional cutter dredge is less than the study region boundary depth of 90 m (300 ft).

Unit costs for dredging glory holes are given in Figure 4.1-5 as a function of water depth prior to dredging. The costs are based on the use of a cutter suction dredge and are presented for in-situ volumes prior to dredging.

5) Dredging of pipeline trenches

A pipeline trench will have a bottom width of 3 to 6 m (10 to 20 ft) with as steep a side slope as possible. The depth of the trench varies depending on the water depth and the requirement to provide sufficient embedment in the seabed to avoid damage to the pipeline by scouring ice features. For a further discussion of burial requirements refer to Section 7.1, "Marine Pipelines." The length of the

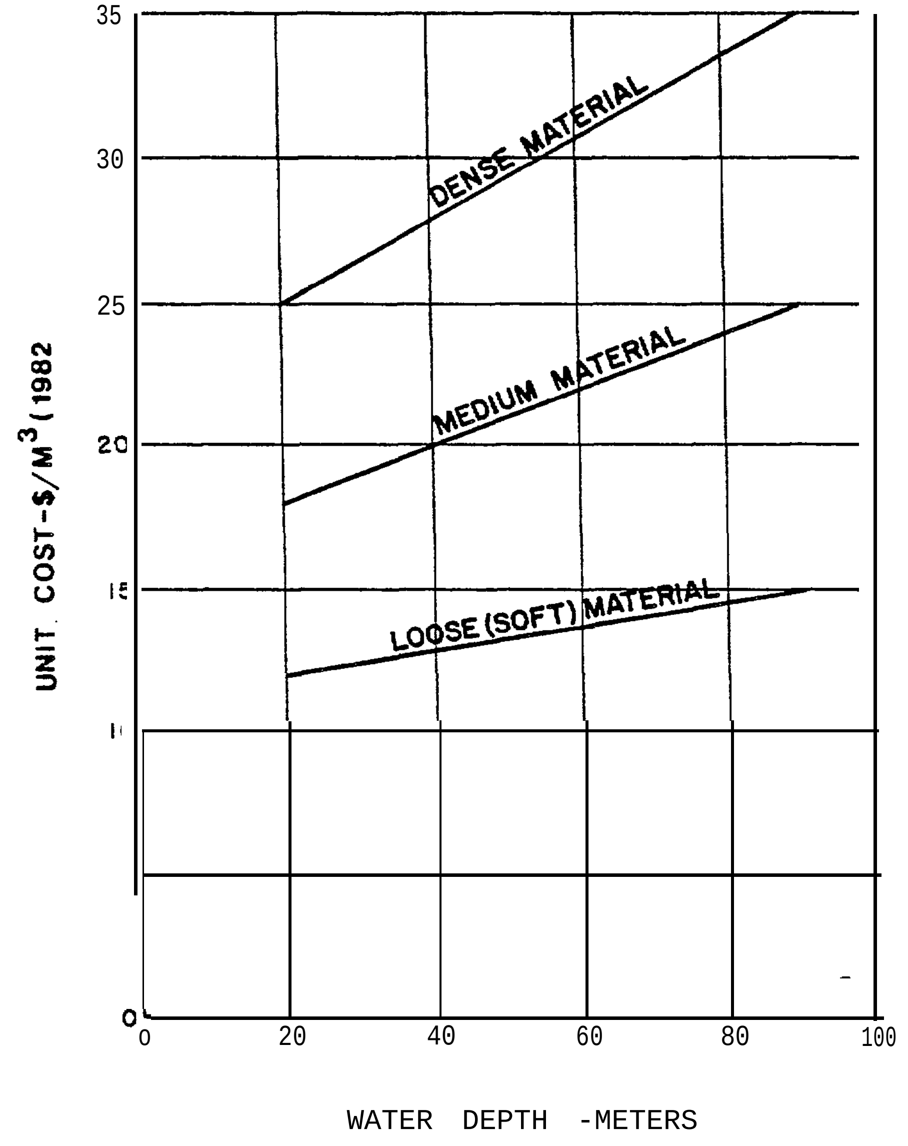

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Figure 4.1-5. Unit cost of dredging a glory hole versus water depth.

pipeline can be considerable and the material to be dredged can be any material present in the study area, including permafrost. A cutter suction dredge is the most effective type of dredge but existing equipment is not able to dredge such a small profile in the subject water depths and at the progress rates required for the short construction season, therefore, special equipment must be designed to perform this task.

The unit costs for dredging pipeline trenches are given in Figure 4.1-6 as a function of water depth. The costs are based on the use of a cutter suction dredge and are presented for in-situ volumes prior to dredging. The costs are presented on a per $m^3$ basis but it should be borne in mind that the reduced quantities, due to the steeper side slopes that can be achieved in denser materials, tends to offset the higher unit cost of dredging denser materials when considering the cost of the trench on a linear meter basis. Stiff clays will have stable side slopes of approximately 1 on 1 while soft clays and silts require a side slope of 1 on 2.5 and loose sand 1 on 10.

### c) Development of Dredging Unit Costs

The unit costs of dredging operations will vary with some or all of the following factors:

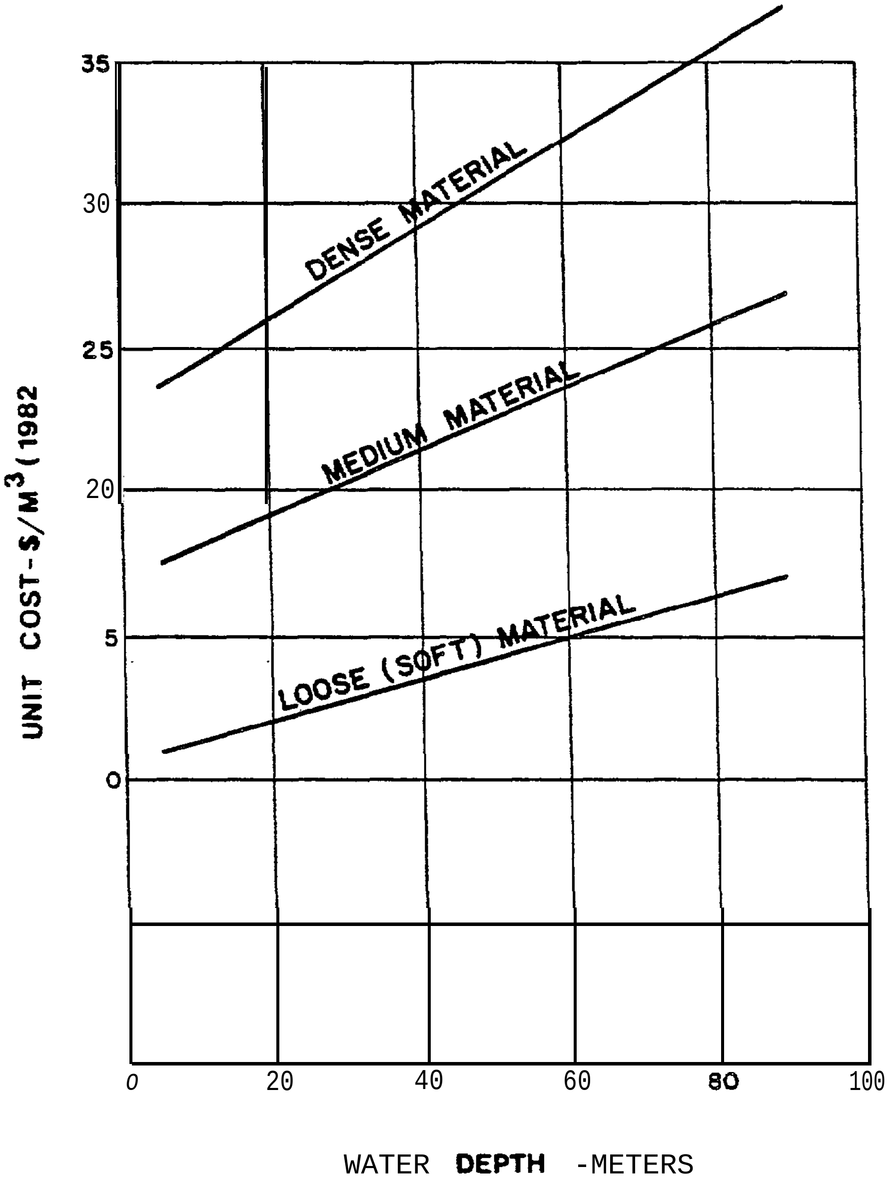

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Figure 4.1-6. Unit cost of dredging a pipeline trench versus water depth.

- borrow area water depth,
- platform location water depth,
- haul distance,
- total volume of dredged material,
- number of working days per season,
- type of dredge,
- type of soil,
- mobilization and demobilization costs, and
- operational period of dredging equipment.

The dredging unit costs presented above have been shown as a function of the factors to which they are most sensitive. They are based on using the most cost effective type of dredging equipment for the type of dredging operation being considered. It is also assumed that dredging will be performed by experienced dredging contractors, bidding on a competitive basis. The unit costs were developed as described below.

- Capital Costs

  As mentioned above, the equipment to be used in Alaska must be built in the United States to comply with current legislation. As a consequence, the investment in equipment will be relatively high in comparison with equipment built in the Far East and Europe. In addition to the normal investment, extra cost is accrued for special Arctic design requirements such as ice strengthening or ice classification.

Contractors can be expected to charge the project with the write-off costs of the special additions and with the write-off of the equipment to such an extent that after release from the project the equipment is competitive for use on other projects. The construction industry is generally not willing to make commitments greater than 3 to 5 years. Therefore, the project will be charged with extremely high depreciation and interest costs. The dredging costs presented above are based on a 5 year operational period.

- Operating Costs

  - Crew

Labor cost in Alaska is extremely high, including subsistence, travel, etc. From union contracts and other available information, the cost per man (average of laborers, welders, operators, etc.) used in this study is approximately $3,300 per week, not including overhead and profit, but inclusive of subsistence and travel costs.

- Maintenance and Repairs

Maintenance and repair costs can be divided into long-term maintenance and short-term running costs such as wear and tear, engine room maintenance, etc. Wear and tear costs in particular depend on the material being handled. Gravel, for instance, will wear outpump casings and pipelines extremely fast, while handling of silt and clay will result in considerably lower replacement costs for these items. For purposes of this study, the long-term maintenance costs were set at 1 percent of the investment cost per year and running costs per cubic meter (cubic yard) of material handled are as follows:

| | |
|---|---|
| • gravel | \$ 1.20 per $m^3$ (\$ 0.90 per $yd^3$) |
| • sand/silt | \$0.60 per $m^3$ (\$ 0.45 per $yd^3$) |

- Insurance

The insurance cost was taken as 1.75 percent of the investment cost per year.

- Fuel and Lubrication

Fuel consumption is a function of installed horse-power. For the purposes of this study, the consumption was set at 3.8 liters (1.0 gal) per installed hp per day. The cost of lubrication was set at 10 percent of the fuel cost. The cost of fuel delivered in a fuel barge was set at $ 0.53 per liter ($2.00 per gal) and including lubrication oil cost, this figure is increased to $0.58 per liter ($2.20 per gal).

- Site Overheads

These costs cover the site offices, shore support, communications, etc. The costs vary with the amount of equipment and the number of activities and was set at an average value of 3 percent of the equipment cost.

- Lay-up/Reactivation

The costs for winter lay-up and summer reactivation only include crew costs. Before the start of the season, the crews will dewinterize the equipment and do as much repair and maintenance work as required to keep the equipment running during the short operational season. Cost of spare parts, etc., are covered in the allowance for maintenance. One to two weeks are required to activate the equipment before the season starts and one to two weeks are required to winterize the equipment. In the winter period the equipment is laid up and no cost other than insurance is incurred. The cost of winterization and dewinterization was set at three weeks crew cost for dredges and two weeks crew costs for tugs and smaller equipment.

- Mobilization/Demobilization

All equipment will be available from the U.S. and therefore must be mobilized and later demobilized around Point Barrow. It will take six weeks to mobilize the equipment from any Gulf Coast area and four weeks from the West Coast. The equipment should be at. Point Barrow around the 1st of July in order to maximize the length of the operational season. All costs incurred will be charged to the project. These costs could include:

- towing costs,
- insurance costs,
- Panama Canal fee (if appropriate),
- harboring costs (fuel stops),
- pilot costs,
- operational cost for self-propelled equipment,
- barge cost (auxiliary equipment).

- Operating Season

The dredging unit costs presented in Figures 4.1-2 through 4.1-5 are based on an average of 50 working days per year for the dredging equipment. Since all costs incurred, such as crew, fuel, equipment, etc., must be charged to the project, these costs are essentially fixed costs for the season. Therefore, unit dredging costs are very sensitive to the number of days per year that the dredging equipment can work. For the deeper water sites, the average number of working days may be considerably less and, at the northern edge of the study area, may be as low as 30 days per year. The effect of the average number of working days on dredging unit costs is shown in Figure 4.1-7. It should be borne in mind that the number of working days in a particular operating season may vary significantly from the average resulting in highly variable actual dredging costs.

### d) Future Dredges and Barges

The design criteria for future dredges and barges which can operate in the 20 to 90 m (65 to 300 ft) depth areas of the Arctic are summarized as follows:

#### 1) Cutter Suction Dredge

| | |
|---|---|
| ● dredging depth | 110 m (350 ft) |
| ● production capability: | |
| - remove unsuitable soil from site | 1,500 m$^3$/hr (2,000 yd$^3$/hr) |
| - dredge Glory Hole | 1,500 m$^3$/hr (2,000 yd$^3$/hr) |
| - load sand | 3,100 to 3,800 m$^3$/hr (4,000 to 5,000 yd$^3$/hr) |
| - strip overburden | 3,100 to 3,800 m$^3$/hr (4,000 to 5,000 yd$^3$/hr) |

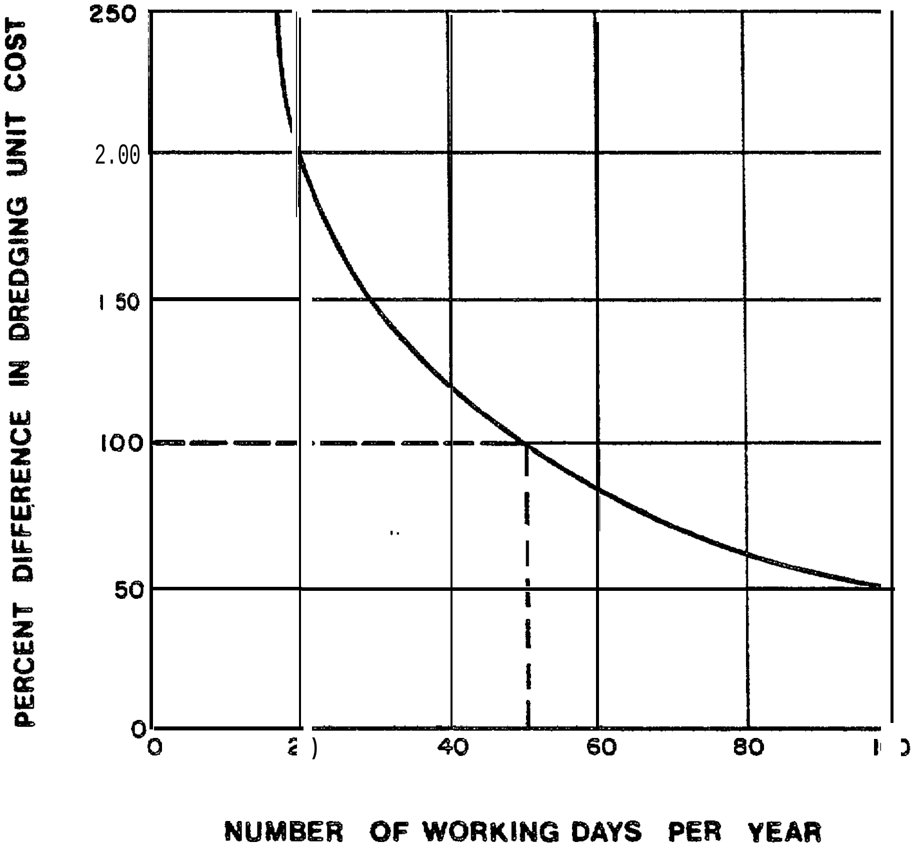

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Figure 4.1-7. Effect of number of working days per year on dredging unit cost.

2) Stationary Dredge

| | |
|---|---|
| ● dredging depth | 110 m (350 ft) |
| ● production capability | 3,100 to 3,800 $m^3$/hr (4,000 to 5,000 $yd^3$/hr) |

3) Trailer Suction Hopper Dredge

| | |
|---|---|
| ● hopper capacity | 6,100 to 12,200 $m^3$ (8,000 to 16,000 $yd^3$) |
| ● number of pumps/arms | 2 |
| ● loading time | 1 hr |
| ● dredging depth | 100 to 110 m (330 to 350 ft) |
| ● sailing speed | 15 to 16 knots |

4) Self-Propelled Barge

| | |
|---|---|
| ● hopper capacity . | 3,100 to 3,800 $m^3$ (4,000 to 5,000 $yd^3$) |
| ● sailing speed | 13 to 14 knots |

5) Towed Barge

| | |
|---|---|
| ● hopper capacity | 3,100 to 3,800 $m^3$ (4,000 to 5,000 $yd^3$) |
| ● sailing speed | 7 to 8 knots |
| ● tug power | 4,000 to5,000 hp |

6) Pipeline Trenching Equipment

| | |
|---|---|
| ● dredging depth | maximum 100 m (330 ft) |
| ● operation speed | 1.8 to 2.8 km/day (1 to 1.5 mi/day) |
| ● pump capacity | 119,000 to 138,000 $m^3$/day<br>(156,000 to 180,000 $yd^3$/day) |

Each piece of equipment should be ice strengthened or under ice class. Also, each dredge should:

- have accommodations on board for the entire crew,
- be equipped with a helicopter platform, and
- comply with all U.S. regulations (Coast Guard, Public Health, etc.) and with those of the appropriate classification society.

### e) Dredge Wintering Requirements

During the winter season, dredging equipment should be moved to a safe anchoring place for protection against shifting ice masses. A suitable location, for instance, would be inside the chain of barrier islands. However, the water depth is restricted and it may not be possible to moor the deeper draft trailer suction hopper dredges at such a location. In the event that the barrier islands are too far from the construction site, artificial barriers could be built in an area where suitable fill materials are available. A cutter suction dredge or a stationary dredge would be suitable for this type of work.

Such a staging area would require protection from three sides and a minimum water depth of approximately 7.5 m (25 ft). The structure would likely take the form of a horseshoe and could be built as a berm reaching just above the water level. A representative sketch for such a berm is shown in Figure 4.1-8. Some 153,000

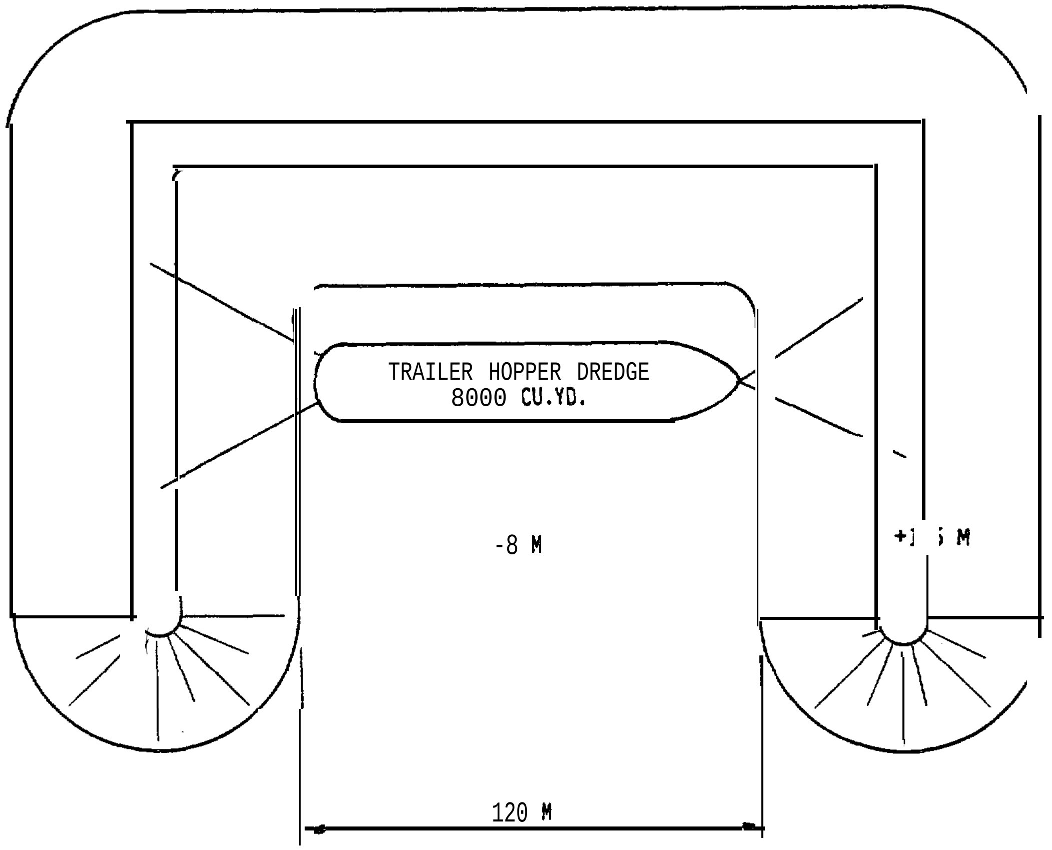

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Figure 4.1-8. Winter staging area for dredging equipment.

$m^3$ (200,000 $yd^3$) would be needed to build the berm. With onshore material, the cost would be approximately $6 million. If small dredging equipment is available and borrow materials could be found at the site, then the cost could be reduced to approximately $3 million.

### 4.1.3 Towing Large Offshore Structures

Most of the drilling and production platforms to be used in the deeper waters of the Beaufort Sea will be built in ice-free locations and towed to the site. Large, high-powered ocean-going tugs will be used to tow the structures at speeds of 3.5 to 7 km per hr (2 to 4 knots). Depending on the size of the structure being towed, two or more tugs will be employed on the voyage. Relatively little power is needed to actually move the structure in calm open water (no ice) with light head winds, and the voyage to the Beaufort area will be planned to take advantage of a fair weather "window" in the summer when such towing conditions might be expected. However, the size and cost of the structures and the adverse impact that their loss or stranding would have on development of the oil fields dictates that the tug power provided must enable the tow to withstand any wind and sea forces that might possibly be encountered. The tow will be comprised of multiple tugs to obtain the requisite power to stabilize the tow under severe storm conditions with wind velocities of 40 to 50 m per sec (80 to 100 knots) and large waves. The multiple tugs also permit directional stability of the tow to be achieved at sea and assist in the precise final positioning of the structure at the site.

The dimensions and displacement of the exploration and production structures vary significantly with the shape and operational water depth of the different concepts. The estimates of towing requirements and costs are based on the assumption that the structures are essentially cylinders towed with the axis vertical and with a grid consisting of vertical plates extending approximately 2 m below the bottom of the structures.

The structures probably will be built abroad thus permitting the use of foreign-flag tugs. If the structures are built in the United States, U.S.-flag tugs will be required for the tow.

The cost estimates assume that large ocean-going tugs with 22,000 hp each will be used for the tow and that the number of tugs required is based on the safety requirements for extreme weather conditions. Figure 4.1-9 presents the approximate towing horsepower required versus displacement of the structure being towed. This figure is approximate because the required towing horsepower also depends on the configuration and characteristics of the structure, but, for preliminary evaluation purposes, it is sufficiently accurate.

The towing cost estimates for two representative structure sizes

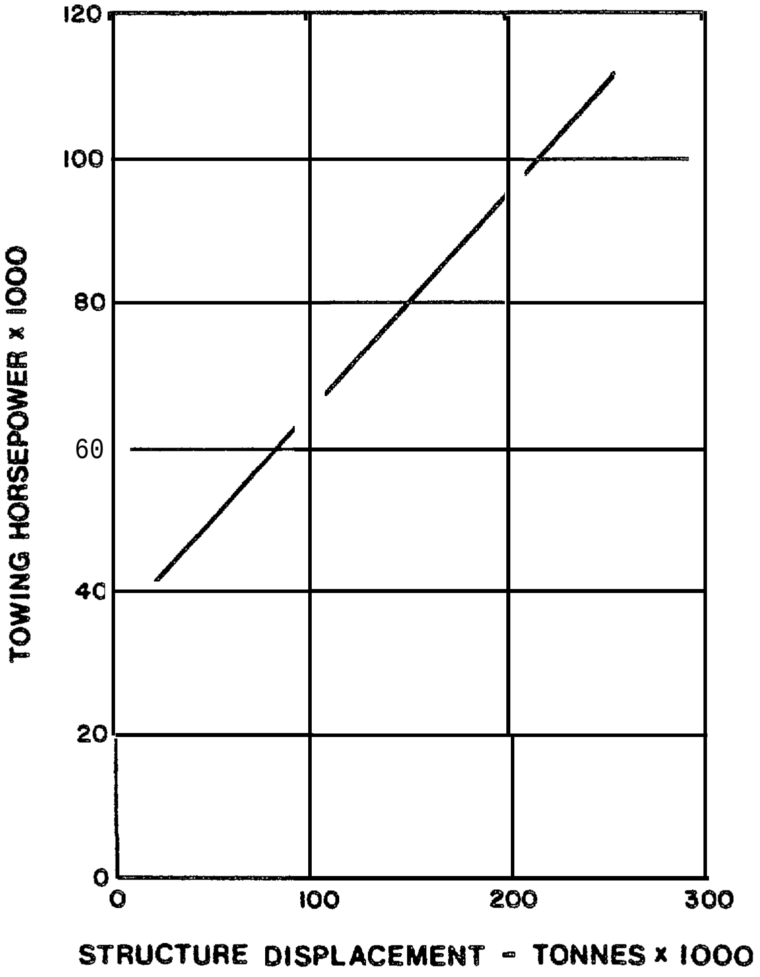

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**Figure 4.1-9.** **Towing** horsepower **versus** structure displacement.

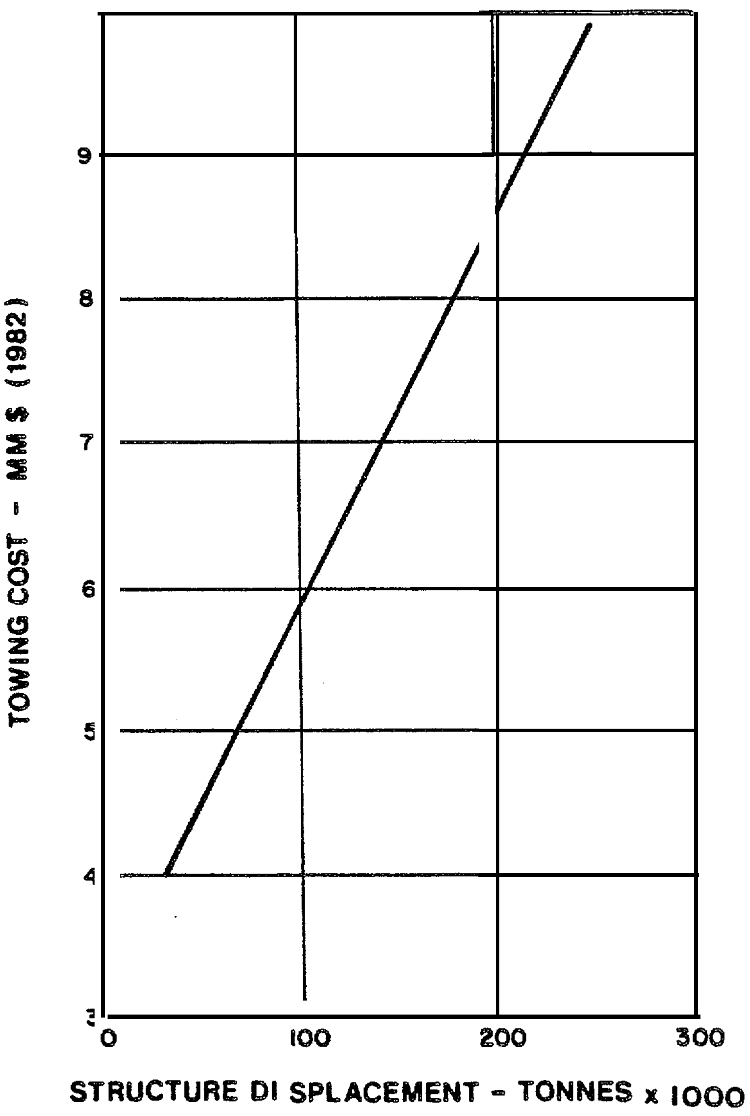
are as follows:

| | Minimum Size | Maximum Size |
|---|---|---|
| Diameter, m (ft) | 100 (330) | 200 (660) |
| Displacement, tonnes | 30,000 | 250,000 |
| Voyage Distance, km (naut mi) (Japan to Beaufort) | 6,400 (3,500) | 6,400 (3,500) |
| No. of 22,000 hp tugs required | 2 | 5 |
| Towing Speed, km/hr (knots) | 5.5 (3) | 5.5 (3) |
| Voyage Time (days): | | |
| At Sea | 49 | 49 |
| Port Time (7 days at origin, 7 days at arrival) | 14 | 14 |
| Delays at 10% | 6 | 6 |
| Mobilization/Demobilization | 10 | 10 |
| Total Time | 79 | 79 |
| Total Cost of Tow (Tug hire @ $25,000/tug/day) | $4.0 million | $9.9 million |
| Towing Cost, per km (naut mi) | $600 ($1,100) | $1,500 ($2,800) |

Using the assumptions indicated in the above estimate, Figure 4.1-10 has been developed to illustrate approximate towing cost versus structure displacement.

### 4.1.4 Structure Concepts and Prefabrication Techniques

Beaufort Sea exploration and production structures, other than artificial islands, will be prefabricated at warm water sites either



TOWING COST IS BASEDON A VOYAGE LENGTH OF 6,400 KM (3,500 NAUT MI)

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**Figure** 4.1-10. Towing cost versus structure displacement.

on the U.S. West Coast or in the Far East, particularly Japan or Korea. To date, the three prefabricated exploration platforms and the steel caissons for one of the two caisson retained islands (CRI) have been constructed in Japan. The concrete caissons for the other CRI were constructed on the West Coast of Canada. The cost estimates contained in this study are based on the assumption that the structures will be fabricated in Japan.

A number of different structural concepts and structural materials have been used and proposed for Arctic offshore structures. Both steel and concrete have been used as well as composite steel/concrete and hybrid combinations of steel and concrete. The steels used have included various grades of special low temperature steel as well as ordinary steel. Concrete construction has included lightweight, semi-lightweight and ordinary weight concrete, both normal strength and special high strength and both prestressed and non-prestressed.

Typically, steel structures have been designed using a horizontal stiffened-plate/bulkhead system similar to icebreaker designs, but allowing for development of "plastic hinges" in the shell plate. Other, more novel steel structural concepts have also been proposed. Concrete structures have been designed utilizing conventional systems of flat plates, bulkheads and diaphragms and more exotic honeycomb configurations. Composite systems using steel inner and outer plates with concrete filler between have been used or proposed for various modifications of surplus tankers to convert them to exploration structures. The structures may be single integral units or a series of bricks or blocks stacked, either prior to transport to the site or after arrival at the site.

The numerous concepts proposed utilize several different approaches for resisting the ice forces (Gerwick, 1983) including:

- Reducing the global ice force acting on the structure by:
  - presenting a minimum frontal area to the ice;
  - using a cone to force failure in flexure rather than in crushing;
  - intercepting the ice impact at a small point to use up the kinetic energy in local crushing.

- Improving transfer of shear and overturning forces from the structure to the soil by:
  - enlarging the base;
  - intercepting the deeper draft ice well below the waterline to reduce the overturning moment;
  - intercepting the ice floe on a conical surface to force the ice to ride up and hence increase the force acting downward on the soil, which increases resistance to sliding.

- Improving the soils by:
  - dredging the weak surface soils and replacing with sand and gravel;
  - surcharging the soils while using wick or sand drains to accelerate consolidation;
  - vibratory consolidation of loose surface sands;
  - freezing;
  - injecting sand or grout under the caisson to ensure full contact.

- Providing supplemental mechanical transfer of shear to the soil:
  - with steel skirts;
  - by sinking the structure down through weak surface soils using bridge pier caisson techniques;
  - using spud piles driven or jacked down through the weak soils to stronger soils below.

Depending on the dimensions of the structures, they can be fabricated either on a barge, in an existing graving dock or in a specially constructed, temporary graving dock. The structures, particularly if steel, may be completely fabricated in the graving dock prior to being floated. Concrete structures, with their greater draft, would probably be fabricated in the graving dock only to the point where the exterior walls are sufficiently high to permit the structures to be floated. They would then be removed from the dock and finished afloat.

In general, the techniques required for fabrication of offshore Arctic structures are well established. The extremely high loading to which these structures are subjected requires an unusual degree of stiffening or reinforcing and consequently thorough quality control is extremely important. Casting of high-strength, lightweight concretes and welding of low temperature steels are just two of the areas that require special quality control attention.

## 4.2 TOPSIDE EQUIPMENT, SPACE AND MANPOWER REQUIREMENTS AND COSTS

The purpose of exploration and production platforms is to support the equipment, supplies and quarters (jointly referred to as topsides) required to drill for and produce oil. The weight and space requirements, as well as the cost, of the topsides is an important factor affecting the overall cost of the platforms. Since the nature and function of the topsides for exploration and production platforms are quite different, they are treated separately below.

### 4.2.1 Exploration Platforms

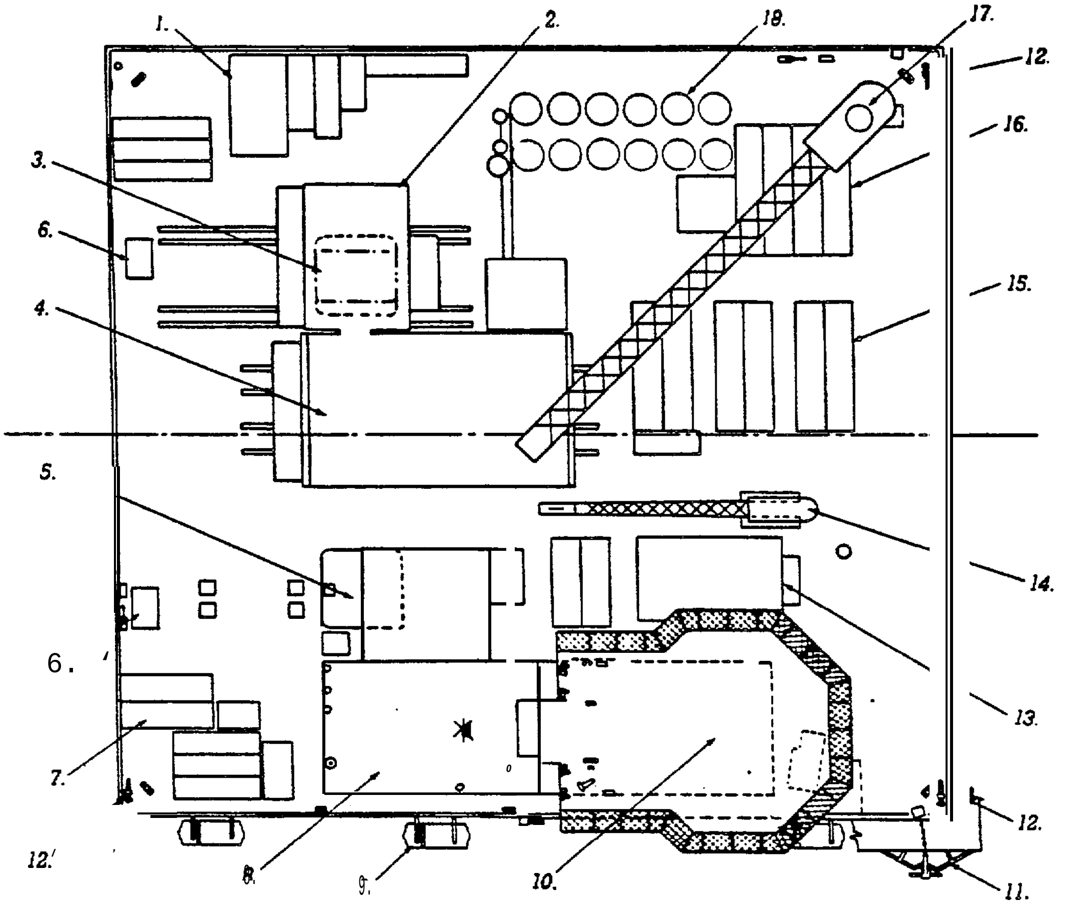
The topsides portion of a Beaufort Sea exploratory drilling platform consists of a modularized, winterized drilling rig package supported by stored tubular goods, cement and mud systems, testing and wire line units, cranage, living quarters and helideck. The rig package itself includes the mast, power supply, BOP system, drill string, air compressors, etc. The equipment for artificial islands, bottom founded structures and floating systems is essentially the same except that, due to weight limitations and stability requirements, floating systems have less storage capacity for drilling consumables. Typically, bottom founded systems have sufficient storage capacity to drill two to three wells without resupply, the storage capacity of artificial islands will depend on the particular drilling plan for the island and floating systems will have storage capacity for drilling at most one well. A typical topsides layout for a bottom founded exploration platform is shown in Figure 4.2-1.

The total dry weight for the topsides equipment for a bottom founded system, including rig package, quarters, consumables and tubulars is approximately 10,000 tonnes. The equivalent weight for a floating system would be less than 4,000 tonnes. The minimum deck area required for a bottom founded structure is approximately 6,000 $m^2$ (65,000 $ft^2$).

The manpower required to operate any of the three categories of exploration platforms is virtually the same and ranges between 90 and 100 people. This manpower is based on two 12 hour shifts daily. The rotation factor of the crew varies among the different operators and contractors but, on average, it appears that oil company personnel usually work on a two-week-on/two-week-off basis while contractors usually work on a two-week-on/one-week-off basis.

Cost estimates for typical exploration platform topsides are given in Table 4.2-1 and have been developed from the following sources:

- Budget quotes with accompanying weight, size and delivery times solicited from vendors.
- Inhouse cost information from recent projects and recent studies.



1. TEST SEPARATOR
2. SUBSTRUCTURE
3. DRILLING WELL
4. PIPE HANDLING
5. SERVICE WELL
6. BOOBY HATCH
7. DRILL PIPE
8. QUARTERS
9. SURVIVAL CAPSULE
10. HELI DECK
11. ANCHOR
12. SW SPRAY MONITOR
13. SHOP
14. CRANE (MOVABLE)
15. CASING STORAGE
16. CASING STORAGE
17. CRANE (PEDESTAL)
18. BULK MUD AND CEMENT TANKS

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Figure 4.2-1. Typical exploration platform topsides layout.

- Where information was not available by either of the two methods above, equipment and material weights, sizes and costs were prorated from data available for similar items of another size.

## TABLE 4.2-1

## EXPLORATION PLATFORM TOPSIDES CAPITAL COST

| Item | Artificial Islands | Bottom Founded | Floating |
|---|---|---|---|
| | IN-PLACE COST, MM $ | | |
| Management and Engineering | 1 | 1 | 1 |
| Drilling Equipment | 17 | 17 | 17 |
| Other Topsides | 5 | 5 | 5 |
| Below Deck Equipment | | 9 | 9 |
| Transportation, Installation, Removal | 15 | Incl w/ Platform | Incl w/ Platform |
| Certification and Insurance | 1 | 1 | 1 |
| Total | 39 | 33 | 33 |

Topsides costs are assumed to be amortized over the same period of time as the exploration platforms, which is three years for artificial islands and bottom founded structures and six years for floating platforms.

The daily cost of manpower and consumables while drilling is discussed in Section 4.3.1, Exploration Wells.

### 4.2.2 Production Platforms

The topside facilities for production platforms are based on the crude oil production parameters listed in Section 3.3. The base case total production rate for the platform has been assumed to be 200,000 BPD. As stated in Section 3.3, this requires a total of 68 wells on the platform (assuming all wells are drilled from the platform and no subsea satellite wells are used). In order to drill that number of wells within a reasonable period of time, two drilling rigs are required on the production platform.

To investigate the sensitivity of production topsides weight, space requirements and costs to the total platform production rate, 100,000 BPD and 300,000 BPD production rate cases were" also evaluated. For the 100,000 BPD case, only 34 wells will be required and one drilling rig on the platform is sufficient. It is assumed that for the 300,000 BPD case a number of the wells will be satellite, subsea completions and two drilling rigs on the platform will be sufficient.

A processing system was developed for the three production rates, including an evaluation of auxiliaries and utilities. The simplified production block flow diagram that was developed is shown in Figure 4.2-2. Based on this flow diagram, equipment lists were prepared on a system-by-system basis for each production rate for the following major systems:

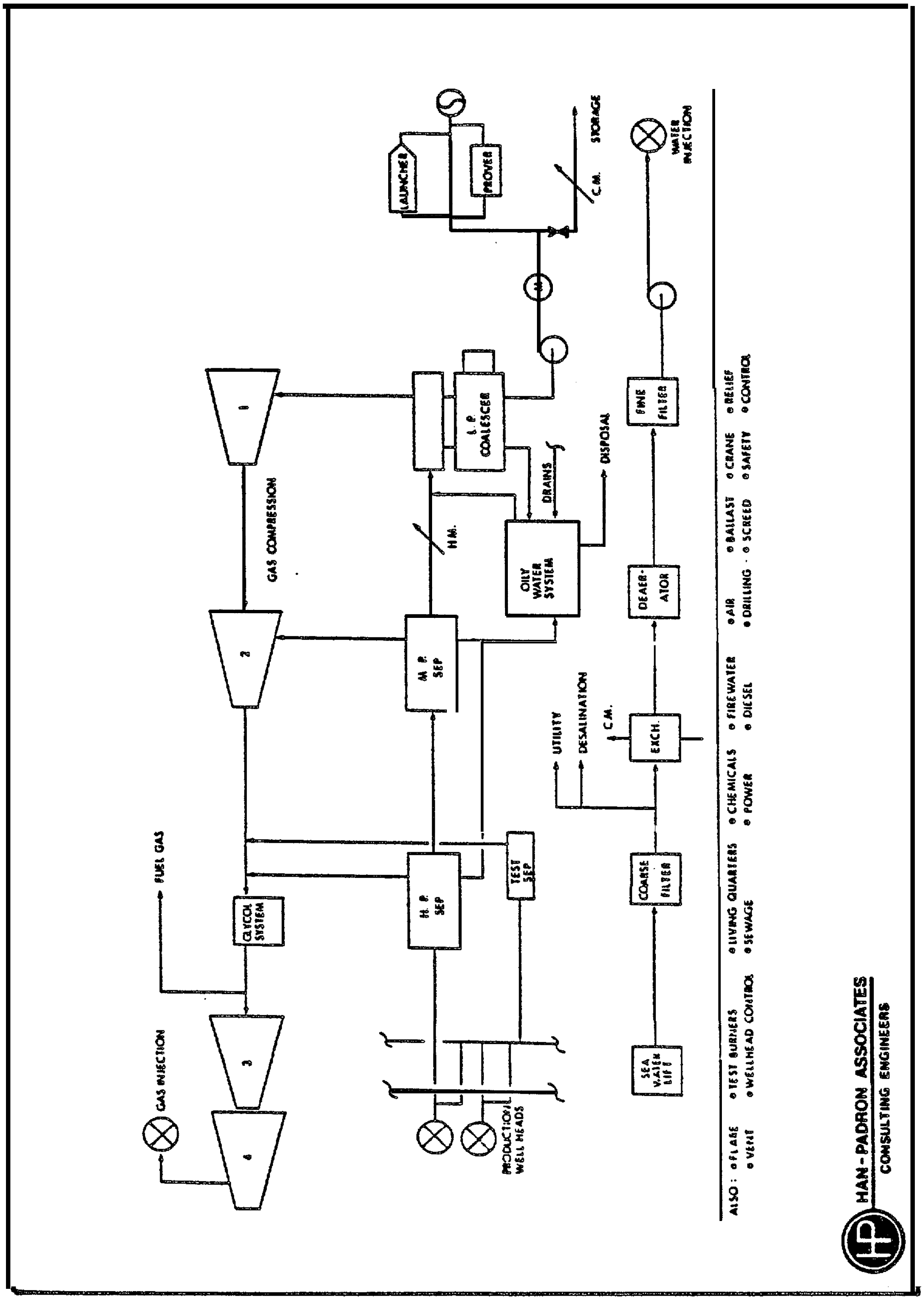


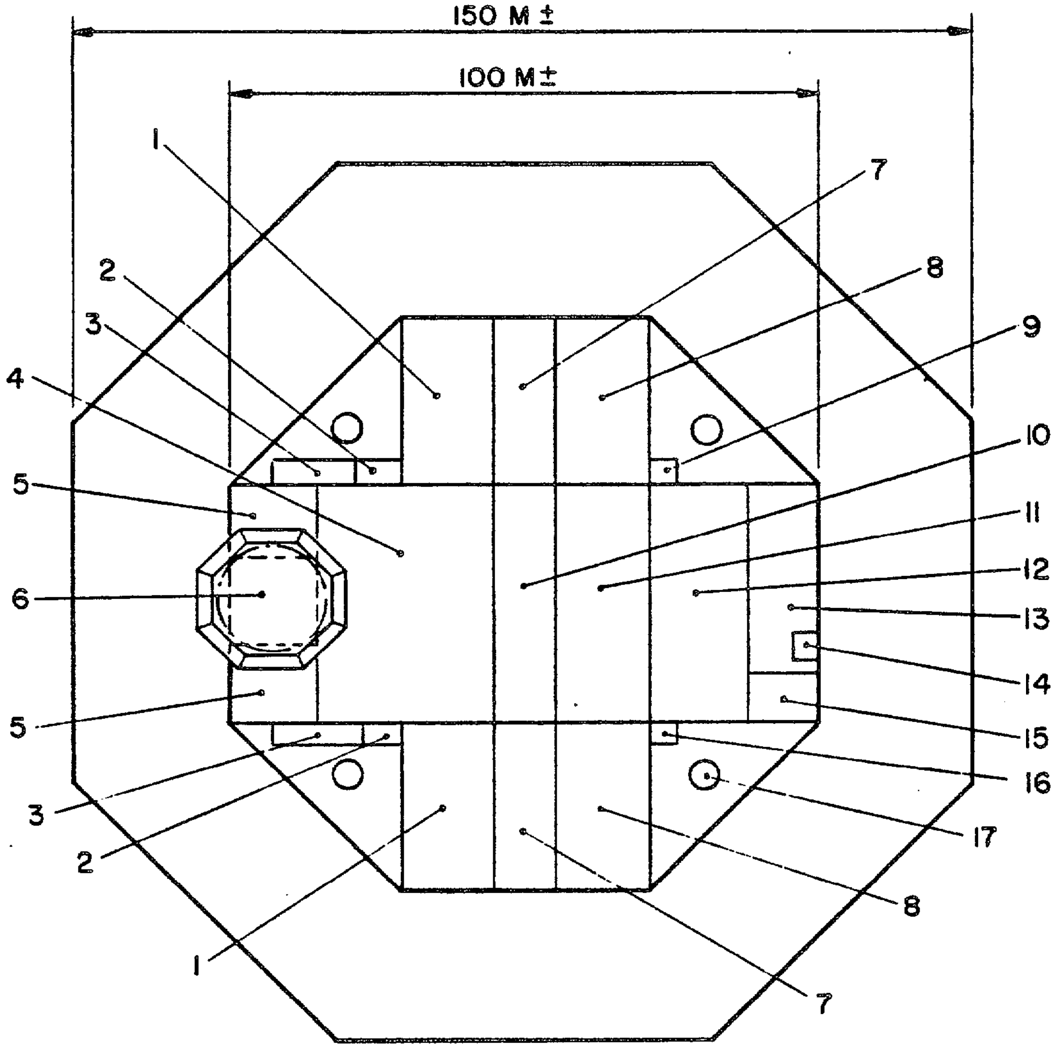
Figure 4.2-2. Typical production blockflow diagram.

- oil and gas separation,
- crude oil,
- gas compression,
- fuel gas,
- flare and vent,
- glycol ,
- utility water,
- oily water,
- air,
- wellhead,
- drilling,
- water injection, and
- firewater,
- HVAC ,
- cranes,
- chemical,
- lube oil,
- safety,
- electrical,
- instrumentation,
- piping,
- maintenance,
- diesel ,
- buildings/structures.

A typical generalized topsides layout for a production structure with two levels for equipment and two development drilling rigs is shown in Figures 4.2-3 and 4.2-4.

To establish the weight, size and cost of the topside equipment, three methods were used:

- Budget quotes with accompanying weight, size and delivery times solicited from vendors.
- Inhouse cost information from recent projects and recent studies.
- Where cost information was not available by either of the two methods above, equipment and material weights, sizes and costs were prorated from data available for



1. DRILLING AREA, PUMPS & TANKS
2. FUEL GAS
3. HEAT MEDIUM
4. GAS SEPARATION & GAS TREATMENT
5. LIVING QUARTERS (2 LEVELS)
6. LIVING QUARTERS (3 LEVELS), CONTROL CTR/ COMM./NAVIGATION/SAFETY (2 LEVELS)
7. WELLHEAD AREA
8. DRILLING AREA & DIESEL POWER
9. STEAM GENERATOR
10. CENTRAL PIPE RACK (3 LEVELS)
11. POWER DISTRIBUTION
12. POWER GENERATION
13. FRESH WATER & SERVICE WATER
14. FLARE STACK
15. INSTRUMENT AIR
16. DIESEL FUEL
17. PINTLE CRANE

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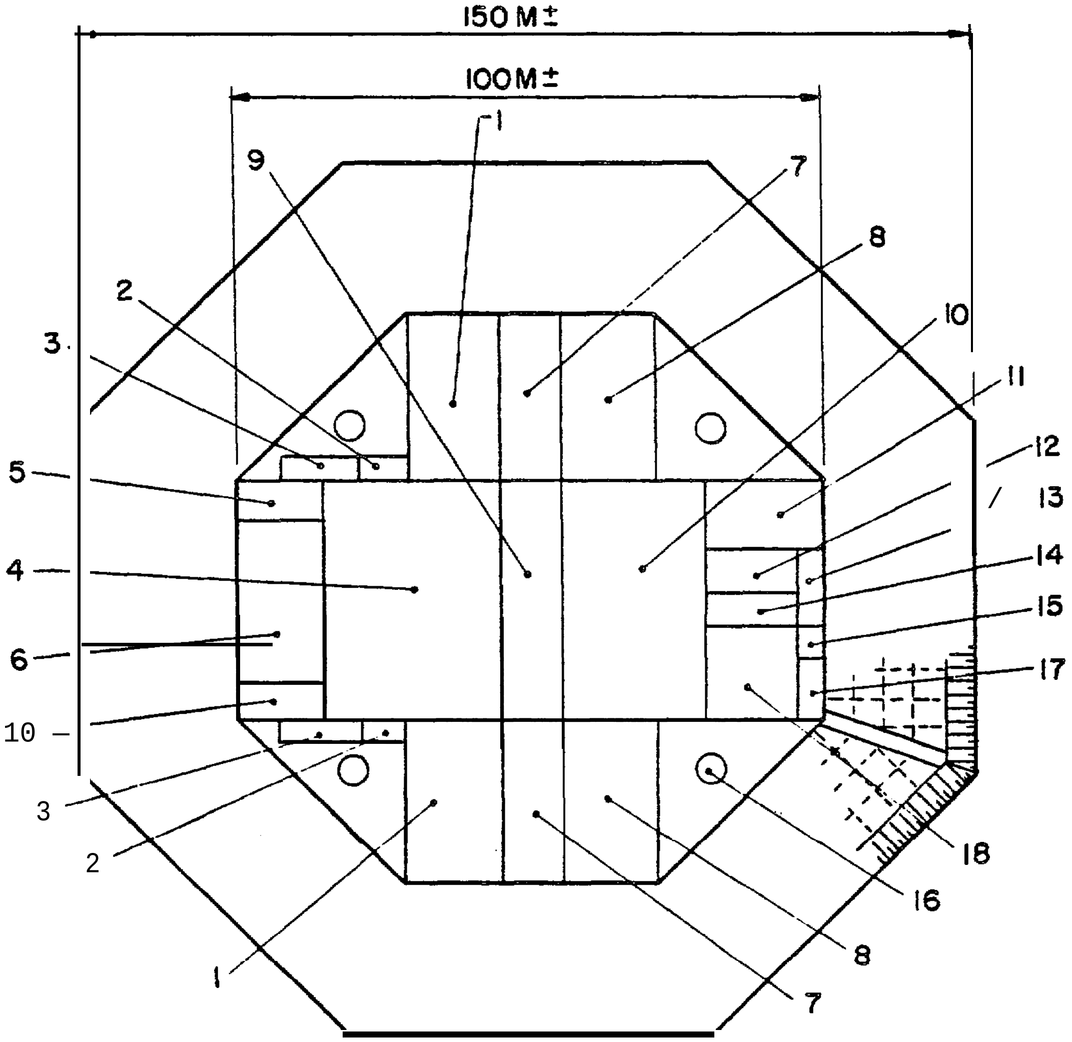
**Figure 4.2-3.** Typical production platform topsides layout, upper level.



1. DRILLING AREA, PUMPS & TANKS
2. FUEL GAS
3. HEAT MEDIUM
4. GAS SEPARATION & GAS TREATMENT
5. CRUDE METERING
6. REFRIGERATION UNIT
7. WELLHEAD AREA
8. DRILLING AREA & DIESEL POWER
9. CENTRAL PIPE RACK (3 LEVELS), MANIFOLD (LOWER LEVEL)
10. GAS INJECTION
11. CHEMICAL INJECTION & CHLORINATION
12. WATER INJECTION
13. SEAWATER
14. FIRE PROTECTION
15. RELIEF FLARE
16. PINTLE CRANE
17. SEWAGE
18. EFFLUENT WATER TREATMENT

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Figure 4.2-4. Typical production platform topsides layout, lower level.

similar items of another size.

The weight of the equipment was tabulated from these sources. Then the weight of the other components was developed based on an established relationship to the weight of the equipment. It was assumed that all equipment would be modularized and the modules fabricated at a location other than the site of fabrication of the platform. The following weight percentages for modularized facilities were used:

| Item | Weight, % |
|---|---|
| Equipment | 45 |
| Steel | 25 |
| Piping | 18 |
| Electrical | 4 |
| Instrumentation | 3 |
| Other (HVAC, fireproofing, insulation, paint) | 5 |

A summary of the topsides weight and area, for the three production rates is given in Tables 4.2-2 and 4.2-3, respectively.

Note that the quarters area indicated in Table 4.2-3 is the plan area of one level. For the 100,000 BPD case, four levels would be required and for the 200,000 BPD and 300,000 BPD cases, five levels would be required. Also note that the drilling area indicated is the area for a platform with one level; for a multilevel platform, that area must be provided on each level.

## TABLE 4.2-2

## PRODUCTION PLATFORM TOPSIDES WEIGHT

|  | Weight (tonnes) |  |  |
|---|---|---|---|
| Item | 100,000 BPD | 200,000 BPD | 300,000 BPD |
| Equipment | 6,500 | 9,000 | 11,000 |
| Module Steel | 4,000 | 5,000 | 6,000 |
| Piping | 2,500 | 3,600 | 4,300 |
| Electrical | 600 | 800 | 1,000 |
| Instrumentation | 500 | 600 | 700 |
| Other | 900 | 1,000 | 1,000 |
| Total Dry Weight | 15,000 | 20,000 | 24,000 |
| Total Operating Weight | 25,000 | 34,000 | 40,000 |

## TABLE 4.2-3

## PRODUCTION PLATFORM TOPSIDES AREA

|  | Area ($m^2$) |  |  |
|---|---|---|---|
| Item | 100,000 BPD | 200,000 BPD | 300,000 8PD |
| Process | 4,500 | 6,500 | 8,000 |
| Utilities | 5,500 | 8,500 | 9,500 |
| Manifolds | 2,000 | 2,500 | 3,000 |
| Quarters | 1,500 | 1,500 | 1,500 |
| Drilling | 1,500 | 3,000 | 3,000 |
| Total Area | 15,000 | 22,000 | 25,000 |

A summary of the manpower required for operation of the production platform for the three production rates is given in Table 4.2-4.

TABLE 4.2-4

PRODUCTION PLATFORM MANPOWER

| | Size of Crew | | |
|---|---|---|---|
| | 100,000 BPD | 200,000 BPD | 300,000 BPD |
| During full drilling operations | 100 | 140 | 140 |
| During full production operations | 150 | 190 | 190 |
| For design of quarters | 220 | 300 | 300 |

Note that full drilling and full production operations do not occur simultaneously.

In order to develop an accurate estimate, the topsides costs were divided into the following major components:

- Engineering and project management
- Equipment and material procurement, including mechanical equipment, pipe/valves/fittings, steel, electrical, instrumentations drilling package, etc.
- Topsides fabrication, including module construction and installation of the equipment and material.
- Module transport, installation and hookup on the structure at a warm-water structure fabrication site. The cost of transporting and installing modules on an

artificial island production platform has been included in the cost estimate for the artificial island.

The costs of the topsides component were developed as follows:

- Equipment and materials: As described above.
- Steel: Average price of $800 per tonne.
- pipe/Valves/Fittings: 75 percent of the piping quantity is estimated to be pipe and 25 percent valves and fittings. Piping average price of $1,200 per tonne. Valves and fittings average price of $25 per kg.
- Freight, duty and taxes at 10 pecent of value.
- Spare parts included in two categories:
  - For startup, 5 percent of the value of the mechanical equipment.
  - For first year spares, 10 percent of the value of the equipment, electrical, instrumentation and valves.

The cost of module fabrication was based on the weights of steel, equipment, and other materials and items by applying established manhour factors as follows:

| Discipline | Hours/Tonne |
|---|---|
| Equipment Installation | 45 |
| Steel Work | 90 |
| Piping (Fabrication & Installation) | 140 |
| Electrical & Instrumentation | 165 |
| Other (Insulating, Painting, etc.) | 12 |
| Hookup, Test & Commission | 30 |
| Loadout & Tiedown | 6 |

First line supervision was added at 10 percent of the craft hours. The fabrication costs were based on an average hourly rate of $50.

Module transport costs from the fabrication yard to the site where the structure is fabricated were estimated as follows:

- Allow 3 modules/barge.
- Allow 2 weeks per tow.
- Allow $20,000 per day for mobilization, demobilization, barge and tug rentals, etc.
- Allow 1 day per barge to load (or unload) 3 modules.
- Allow $75,000 per day for 2,000 ton crane barge.

Module installation and hookup were estimated by assuming that 40 percent of the hours as previously calculated for fabrication of module piping, electrical, instrumentation, other, testing/commissioning and supervision are required for module outfitting at the structure fabrication yard. At the final site it was assumed that 5 percent of the shipyard hookup hours will be required.

The estimated capital costs of production platform topsides are given in Table 4.2-5 for artificial islands and Table 4.2-6 for bottom founded structures. These costs do not include the island or deck structure costs.

The estimated annual operating costs of production platform topsides are $43, $63 and $69 million for the 100,000 BPD, 200,000 BPD and 300,000 BPD peak production rates, respectively. These costs include the cost of manpower, consumables, replacement equipment and workovers, but do not include manpower and drilling consumable costs for development drilling. For those costs refer to Section 4.3.2, Platform Development Wells. As production rates decrease with time, approximately two thirds of the topsides annual operating cost is fixed and the remaining one third is reduced in proportion to the production rate.

## TABLE 4.2-5

## PRODUCTION PLATFORM TOPSIDES CAPITAL COST - ARTIFICIAL ISLAND

| | Cost, MM$ | | |
|---|---|---|---|
| | 100,000 BPD | 200,000 BPD | 300,000 BPD |
| Management and Engineering | 34 | 40 | 41 |
| Drilling Equipment | 17 | 34 | 34 |
| Production and Other Equipment | 99 | 156 | 210 |
| Module Fabrication | 95 | 165 | 180 |
| Transport and Installation | 130 | 200 | 260 |
| Certification and Insurance | 5 | 5 | 5 |
| Total cost | 400 | 600 | 730 |

## TABLE 4.2-6

## PRODUCTION PLATFORM TOPSIDES CAPITAL COST - BOTTOM FOUNDED

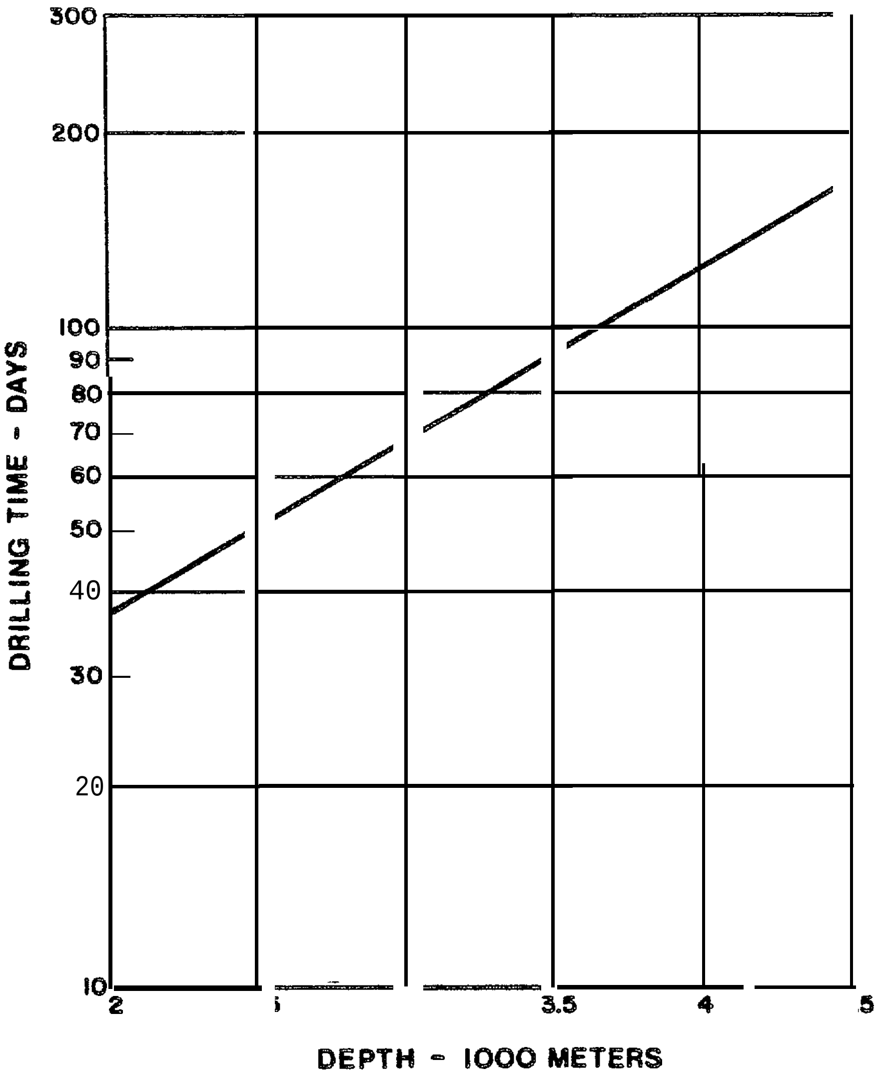
| | Cost, MM$ | | |
|---|---|---|---|
| | 100,000 BPD | 200,000 BPD | 300,000 BPD |
| Management and Engineering | 34 | 40 | 41 |
| Drilling Equipment | 17 | 34 | 34 |
| Production and Other Equipment | 99 | 156 | 210 |
| Below Deck Equipment | 10 | 10 | 10 |
| Module Fabrication | 115 | 165 | 180 |
| Transport and Installation | 20 | 35 | 40 |
| Certification and Insurance | 5 | 5 | 5 |
| Total Cost | 300 | 445 | 520 |

## 4.3 WELL DRILLING TECHNIQUES AND COSTS

### 4.3.1 Exploration Wells

Arctic exploration drilling began onshore in 1961 and gradually moved offshore in the early 1970's. Since then, a number of wells have been drilled from man-made ice, sand and gravel islands in water depths up to approximately 20 m (65 ft). Also, conventional drilling vessels, specially modified, have been utilized in Arctic offshore areas during open water seasons. More recently, prefabricated exploration platforms that can operate year-round and special Arctic exploration systems that extend the operational season compared with conventional vessels have been developed and utilized.

Well drilling from an artificial island or a prefabricated bottom founded structure is essentially the same as drilling on land on the North Slope. Conventional land drilling rigs, modified with low temperature steels and partially enclosed, insulated and heated for the severe environment, are used. Average drilling time from a fixed platform versus true vertical well depth based on historical data (NPC, 1981), is shown in Figure 4.3-1. The drilling time includes rig-up, spud-in, drilling, logging, setting casing, testing, plug and abandoning and rig-down. Drilling from a fixed platform is not significantly affected by wind, wave and ice conditions, but drilling from a floating vessel is affected. Therefore, for floating systems, a weather downtime factor should be applied to the drilling



INCLUDES: RIG-UP, SPUD-IN, DRILLING, LOGGING, SETTING CASING, TESTING, PLUG & ABANDONING, AND RIG-DOW

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Figure 4.3-1. Exploration well drilling time versus well depth.

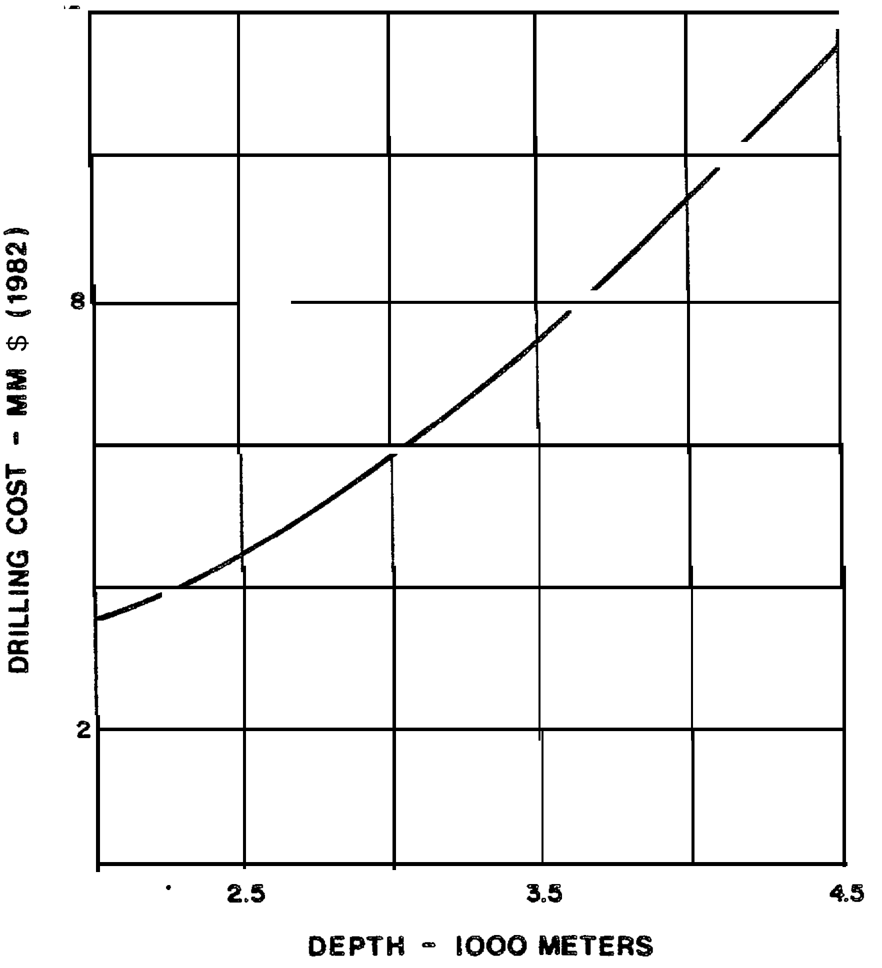
time shown in Figure 4.3-1.

Based on the drilling time shown in Figure 4.3-1, $45,000 per day cost of 95 man drilling crew and $900 per m cost of drilling consumables, Figure 4.3-2 has been developed to illustrate the cost of exploration drilling from an artificial island or bottom founded structure versus well depth. The cost indicated in the figure is the cost of drilling manpower and drilling consumables only and does not include rig amortization and platform costs.

### 4.3.2 Platform Development Wells

No development wells have yet been drilled in offshore Arctic areas. However, development drilling from a platform will be essentially the same as platform drilling in any other location in the world except that the drilling rigs will be modified for the low temperature environment.

Since permafrost can be encountered offshore, Beaufort Sea wells will probably be completed with casing programs, cementing techniques and tubing strings similar to those used in onshore wells on the North Slope. Permafrost subsidence is highly site specific and its impact on casing and platform design can be significant. Because of the high cost per unit of surface area on platforms in the study area, the well spacing used for onshore clusters of wells may not be economically feasible for offshore wells. New techniques will be



INCLUDES: DRILLING MANPOWER AND DRILLING CONSUMEABLES COSTS ONLY

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Figure 4.3-2. Exploration well drilling cost versus well depth.

developed to satisfy the reduced well spacing requirements of offshore facilities.

On artificial islands, development wells can be slant drilled or directionally drilled. The number of wells that can be effectively drilled from an artificial island is limited by the depth and areal extent of the reservoir and the surface area of the island. Prefabricated bottom founded structures have similar limitations. Conical structures may impose a limitation on the number of wells that can be accommodated within the throat diameter, but usually it would be more economical to increase the throat diameter to accommodate the number of wells dictated by the reservoir characteristics rather than provide an additional platform.

In order to drill the large number of wells that will probably be required for a commercial development, two rigs will probably be provided on the platform. Depending on the type of platform and cost of removing a rig, one of the rigs may be removed after development drilling is completed. The second rig would probably remain on the platform for workovers.

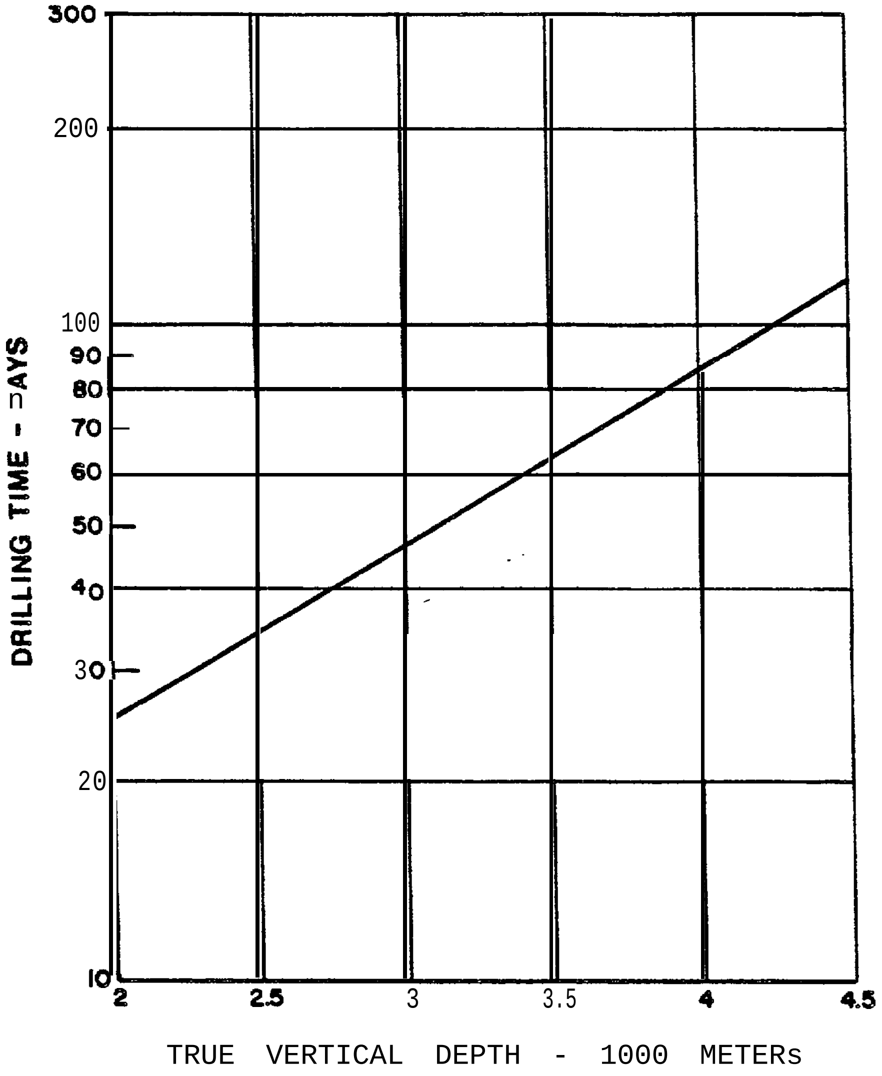
Drilling time per development well is less than for exploration wells due to reduced rig-up and rig-down times and the elimination of testing and plugging time. However, most development wells will be directionally drilled or slant drilled which increases drilling time and drilling costs when plotted against true vertical depth.

Estimated average development well drilling time versus true vertical well depth is shown in Figure 4.3-3. The estimated average cost per well for drilling consumables and drilling crew, versus true vertical well depth is shown in Figure 4.3-4.

### 4.3.3 Subsea Development Wells

Subsea development drilling has been developed throughout the world to produce close to 300 subsea wells (Mohr, 1984). In addition, a significant number of wells have been predrilled through a subsea template prior to placement of a fixed structure over these predrilled wells. In this case, the wells were tied back to a platform and completed in a short period by the platform rig to achieve early production (Brown & Root, 1984). However, subsea development wells in the Beaufort Sea study area pose unique problems and only one subsea well has been completed in the offshore Arctic region (NPC, 1981).

Subsea completions are considered in this study only as clusters of satellite wells with flowlines to the production platform where all processing is carried out. Subsea completions may be economically attractive for shallow or complex reservoirs that cannot be fully developed from a single platform by directional drilling and where their use eliminates the need for additional platforms. They also may offer the opportunity for earlier production since their drilling can be started before the production platform is installed,



CURVE IS AVERAGE DRILLING TIME FOR WELLS
DIRECTIONALLY DRILLED FROM A PLATFORM

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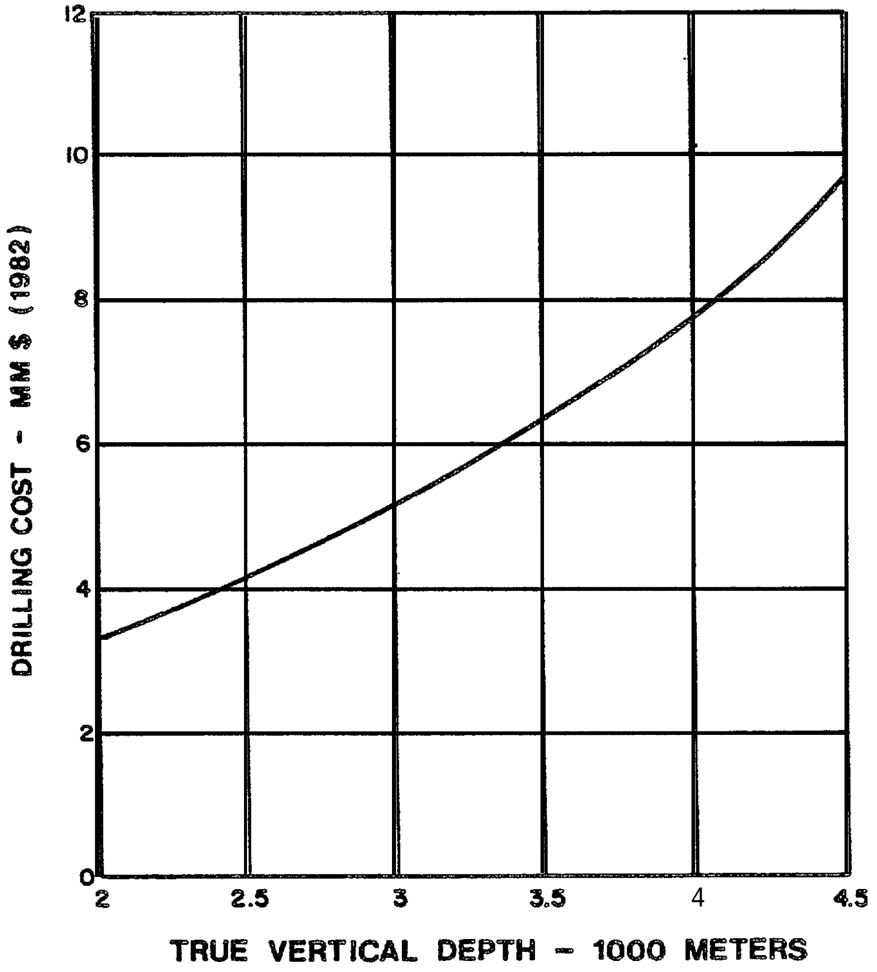
**Figure** 4.3-3. Platform development well drilling time versus well depth.



INCLUDES: DRILLING MANPOWER AND DRILLING CONSUMEABLES COSTS ONLY

BASED ON DIRECTIONAL DRILLING

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**Figure** 4.3-4. Platform development well **drilling cost versus well depth** .

and production can commence as soon as installation is complete and the flowlines connected (assuming the transportation system is operational at this time).

Both "wet" and "dry" subsea production trees are used. The wet system has all of the tree components exposed to ambient seabed conditions. The wet tree completion may be either a diver assisted or diverless design. Divers can perform operations such as wellhead, flowline, and control system connections. Alternatively, a sophisticated system remotely controlled from the surface can be used to make these connections. Historically, wet trees have accounted for most of the subsea completions. The dry system houses all the tree components in a dry, one atmosphere chamber. The chamber is equipped with various penetrators for flowline, hydraulic, and electrical connections. It is also equipped with a service mating port which allows a submersible vehicle to land on the chamber and transfer personnel inside to carry out maintenance functions.

In water depths where the seabed is subject to gouging by pressure ridge keels and ice islands, low profile subsea completions must be used and located at a depth below the mudline which is greater than the potential gouge depth. Preliminary indications are that gouging may occur in water depths up to approximately 50 m (165 ft). For a further discussion of ice gouging, refer to Section 3.1.8. Subsea completions in water depths less than 50 m (165 ft) must be installed in "glory holes," with the depth of the glory hole being a function of the water depth at the site and the height of BOP/wellhead equipment. In a water depth of 30 m (100 ft) the bottom of the glory hole may be 8 or 9 m (25 or 30 ft) below the seabed. For a further discussion of dredging of glory holes refer to Section 4.1.2.

In other areas of the world, subsea clusters are usually drilled from floating platforms (drillships or semi-submersibles) or jack-up drilling platforms. However, in the study area the operational season of these systems, and even specially designed Arctic drillships, is probably too short to permit economic development, drilling and subsea completion. Therefore, subsea clusters would probably have to be drilled from a bottom founded structure, without. a berm. A glory hole, large enough to accommodate the base of the structure, must be dredged before the structure is set in place and the structure would have to be designed for the water depth to the bottom of the glory hole.

It is anticipated that a cluster of 5 or 6 wells could be directionally drilled and completed from a single location in approximately ten months, allowing two months during the open water season for relocation of the platform to another site. The glory hole would be prepared the year before the platform is installed.

All production from the subsea clusters would flow through a flowline bundle to the production platform. The flowline bundle would consist of lines for oil, water, gas and through-flowline (TFL) servicing. All control functions, oil processing and injection water would be supplied from the main production platform.

The cost of drilling manpower and consumables for a subsea well is essentially the same as for a development well from a production platform. However, to the drilling cost must be added the cost of dredging the glory hole, the cost of the drilling platform, and the cost of the subsea template and the flowlines, including burial costs. The platform used for exploration and delineation drilling may not be suitable for subsea development drilling for several reasons including the deeper water depth to the bottom of the glory hole, the need to avoid the use of a berm and the need to drill a greater number of wells from a single location.

While the reliability of subsea installations has not been fully demonstrated for the environment of the study area, it is anticipated that they can be made sufficiently reliable. Therefore, their use will ultimately depend on overall development economics.

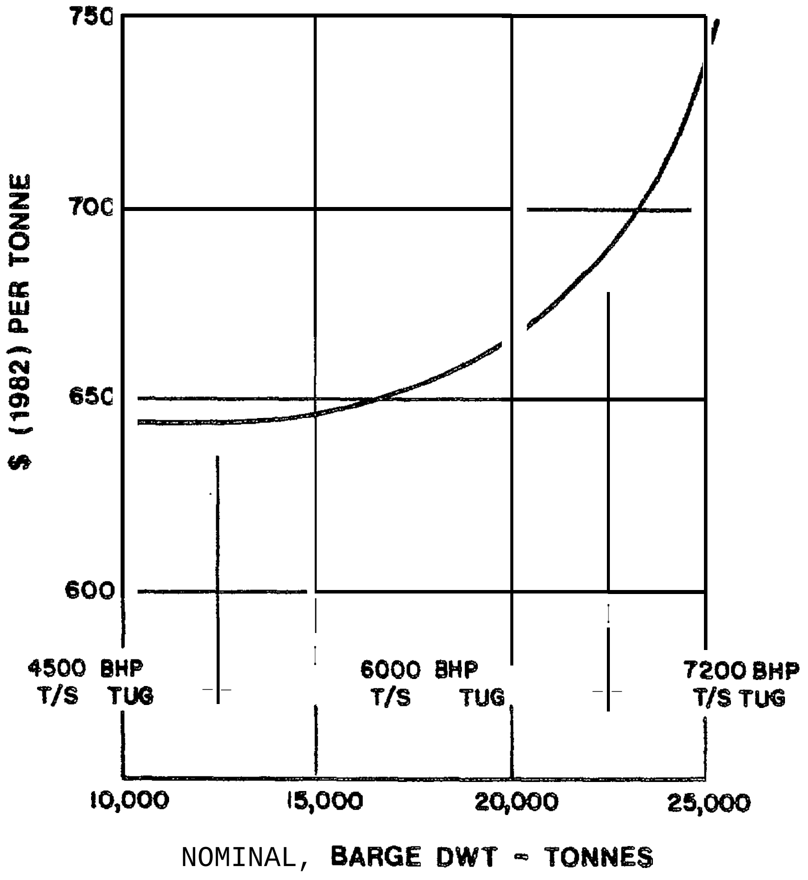
## 4.4 ANCILLARY VESSEL TECHNOLOGY, MANPOWER REQUIREMENTS AND COSTS

### 4.4.1 Supply Tugs and Barges

Oil field supplies, drilling/production equipment and other material requirements will be transported from ports in the contiguous United States to the Beaufort region by tug/barge combinations. It is assumed that procedures similar to those developed by Crowley Maritime Corporation and presently used by that company in its "Arctic Sealift" will be used for projects within the study area. The Sealift operates only during the Arctic summer when the waters in the Beaufort Sea off the Alaskan Coast are relatively ice-free: from about early August until early or mid-September, depending on weather (ice) conditions. The Sealift consists of a flotilla of oceangoing tugs and barges (with one tug towing two barges in tandem) which includes an icebreaking cargo barge and is accompanied by a salvage/rescue vessel. The Sealift flotilla departs from Seattle, Washington, in mid-July and arrives at the edge of the ice pack in the vicinity of Wainwright, Alaska, in about two weeks. When the ice pack moves offshore (in about 1 to 3 weeks, depending on weather conditions), the flotilla, preceded by the icebreaking barge (pushed by one or two tugs, depending on ice conditions), proceeds to the Beaufort base (presently Prudhoe Bay), where the cargo is off-loaded. Cargo discharge is completed in 10 to 12 days and the (normally) empty barges and tugs then depart individually for the return trip to Seattle. Barges have occasionally been delayed discharging at Prudhoe Bay until the ice pack returns with the onset of winter in September and have had to remain trapped in the ice until break-up the following year.

The cargo quantity hauled to Alaska varies from year to year as the oil companies' requirements change. The transportation is provided to the companies on a contractual basis which is proprietary. The cost of cargo transportation from the points of origin in Seattle to the north coast of Alaska has been estimated for a series of tug-barge tows. The results are shown in Figure 4.4-1. The barges are assumed to be deck-cargo barges and have essentially the same proportions as the 18,300 ST (short ton) deck barges used by Crowley in the Arctic Sealift (smaller barges of 12,500 ST DWT also are used in the Arctic Sealift). The installed propulsion power of the twin-screw tugs includes an allowance for limited operation in ice and produces an average speed of tandem tow (hawser towing) of about 16 km per hr (8.5 knots) or 380 km (200 naut mi) per day. The cargo frequently consists of high-volume, relatively low-weight modules which require a wide-beam barge to provide the stable platform needed to reduce the dynamic and acceleration forces encountered in rough seas.

The cargo capacity of the barges is limited to that obtainable with a draft of 3 m (10 ft) because of the shallow water at unloading docks at existing or potential Beaufort Sea base camps. After arrival in the vicinity of the camp, transfer of the barges to the



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*Source:* JJ McMullen

Figure 4.4-1. Freight cost from Seattle to Beaufort Sea.

cargo discharging facility is carried out by small "shuttle" tugs.

The assumptions made in determining the vessel characteristics and the capital and operating costs included in the unit freight cost for the Sealift include:

- All tugs and barges are assumed to return to the loading port at the conclusion of the sealift and that none "winters over" in the Arctic. The *cost* of such a layup is additive to the sealift cost and is variable.
- Homogeneous cargoes are assumed and large volume equipment and structural modules are included in the weight averages for the sealift. This assumption permits the number of barges to be determined from the estimated weight of the sealift.
- Construction costs were obtained from U.S. shipyards. An allowance for pre-delivery expenses and financing with interest cost at 13.5 percent is added to the construction cost to obtain the capitalized cost. The vessels are assumed to have a service life of 15 years. - Operating costs are based on industry and Maritime Administration figures for 1982, adjusted for operation in the severe Arctic environment.
- The freight cost estimates shown in Figure 4.4-1 assume that the vessels are used exclusively for the "Sealift" and that the total annual capital and operational costs are recovered in the Arctic freight rate. These

estimates are based on tug/two-barge tandem units, with allocated allowances for a two-tug icebreaker barge unit, a salvage vessel and aerial reconnaissance

- The total voyage time from Seattle to the Beaufort Sea and return is about 90 days, depending on ice conditions. The capital and operating costs in the study are based on a total time of 150 days to include assembly of the sealift and other time requirements.
- U.S.-flag barges and tugs, using vessels built and documented in the U.S., are used for the sealift from U.S. ports. Foreign-flag vessels could be used if supply cargoes originated in foreign countries.

Figure 4.4-1 shows that the unit freight cost ($/tonne) is approximately level with increasing barge size up to about 15,000 DWT, at which point this cost increases. This is because the higher construction and operating costs of the large barges cannot be offset by substantially more cargo capacity due to the 3 m (10 ft) draft restriction. Inspection of the vessel characteristics in Table 4.4-1 reveals this clearly: the nominal DWT and the costs of the largest barge are 2.5 times those of the smallest barge but the cargo capacity with the draft limited to 3 m (10 ft) is only about 50 percent greater. The unit cost penalty is acceptable because the large cubic volume of some of the cargo transported to Alaska requires considerable deck area not available on the smaller barges.

TABLE 4.4-1

PRINCIPAL CHARACTERISTICS OF BEAUFORT SEALIFT VESSELS
(Dimensions In Meters)

| DEADWEIGHT tonnes | LENGTH 5P | BREADTH | DEPTH | DRAFT | CARGO CAPACITY* tonnes | CAPITAL COST MM$ | OPERATING COST MM$/YR |
|---|---|---|---|---|---|---|---|
| DECK BARGE | | | | | | | |
| 10,000 | 102 | 25.5 | 5.2 | 6.4 | 4,500 | 5.2 | 0.25 |
| 15,000 | 117 | 29.5 | 5.8 | 7.3 | 5,500 | 7.8 | 0.32 |
| 20,000 | 130 | 32.5 | 6.4 | 7.9 | 6,300 | 10.3 | 0*40 |
| 25,000 | 139 | 35.0 | 7.0 | 8.8 | 6,700 | 13.3 | 0.46 |
| ICEBREAKING DECK BARGE | | | | | | | |
| 8,900 | 95 | 32.5 | 5.8 | 4.9 | 6,500 | 7.1 | 0.25 |
| TUGBOATS (Twin Screw ) | | | | | | | |
| 4,500 BHP | 37 | 10.4 | 5.8 | 5.2 | | 6.4 | 1.06 |
| 6,000 BHP | 39, | 11.3 | 5.8 | 5.2 | | 7.4 | ..1.10 |
| 7,200 BHP | 39 | 11.3 | 5.8 | 5.2 | | 8.3 | 1.14 |
| SALVAGE VESSEL (Twin Screw) | | | | | | | |
| 2,250 BHP | 59 | 16.2 | 4.3 | 3*7 | | 2.8 | 0.56 |

* Based on 3 m maximum draft.

### 4.4.2 Offshore Supply and Ice Management Vessels

The supplies and equipment required for the development and production of Beaufort Sea hydrocarbons will be transported by sealift to a suitable base on the Alaskan Beaufort Sea Coast, as described in Section 4.4.1, and distributed to the offshore drilling and production platforms by ice-class support vessels. The vessels will be multi-functional and be capable of performing the basic supply function as well as ice management and ice breaking, anchor handling, towing and rescue/salvage operations. Icebreaking vessels, capable only of performing ice management or rescue/salvage tasks, probably will not be used. The vessels perform an ice management role by moving in circles updrift of the exploration platforms to break the ice into manageable rubble which will move with the current and wind to flow past the structures without imposing high loads.

The power, structural strength and size of the vessels will depend primarily on the length of the season during which they are expected to operate. The Canadian government has established the Canadian Arctic Shipping Pollution Prevention Regulations (CASPPR) defining the structural and power requirements for different zones within the Arctic. Ice conditions within the U.S. Beaufort Sea are comparable to Zone 4 of the CASPPR. The CASPPR provide that, for year-round operation in Zone 4, a vessel built to the structural and powering requirements for ice Class 8 would be needed. This means that the vessel must be able to maintain steady forward progress of three knots when operated individually (with no external icebreaking support) in continuous first year ice eight feet thick. For purposes of this study it has been assumed that a vessel built to Class 6 could operate approximately nine months per year within the study area and a vessel built to Class 4 could operate approximately six months per year. It must be borne in mind that these estimates are based on extremely limited operational data. Considerable research and data gathering is in progress which may require significant revisions of these estimates.

Selection of the economic optimum Class vessels for a particular exploration and/or production scenario requires a detailed evaluation of the benefits derived from increasing the Class of the vessels (less storage required on exploration and production platforms, extended drilling season for floating exploration systems) versus the increased cost of the vessels. Such an evaluation must be made on a site-specific basis and is beyond the scope of this study. For purposes of this study, and based on an analysis of existing Arctic operations, Table 4.4-2 indicates the Classes and numbers of vessels that have been assumed.

TABLE 4.4-2

CLASSES AND NUMBERS OF ICE MANAGEMENT/SUPPLY VESSELS

| Vessel Class | No. of Vessels | Function |
|---|---|---|
| 4 | 2 | Support for all types of artificial island and bottom founded exploration platforms. |
| 4 | 3 | Support for ice-capable floating exploration platforms. |
| 6 | 2 | Support for all types of production platforms when a pipeline transportation system is used. |
| 8 | 2 | Support for all types of production platforms when a tanker transportation system is used. |

If a tanker crude oil transportation system is utilized, the tankers will be sufficiently powered to have but minor problems completing passage to the offshore or nearshore loading terminals. However, due to the size of the vessels and the surrounding, confining ice field, tanker maneuverability will be limited and the most ice-capable tanker could be slowed and eventually stopped by a heavy concentration of large ridges. Therefore, icebreaker assistance may be required on occasion for breakout of beset tankers and Class 8 icebreakers are required for this function, as indicated above.

The most powerful icebreakers in the world, the Soviet Union's 75,000 hp nuclear-powered Arktica (renamed the Leonid Brezhnev) and Sibir, are Class 7 (McKenzie and Johansson, 1979). No other nation has a vessel beyond Class 4 in operation, apart from the American 60,000 hp Class 6 Polar Star and Polar Sea. The maximum specification icebreaking supply vessels currently operating for petroleum development in the Arctic are Class 4 and are not used during the severe Arctic winter.

Since the icebreaker supply vessels must be highly maneuverable in heavy ice conditions and capable of moving quite rapidly through the ice field, they cannot be designed based entirely on ice thickness but must include a sufficient allowance for negotiating pressure ridges. In order to develop cost data for icebreaker supply vessels, shaft horsepower and basic vessel dimensions were developed. The estimated shaft horsepower is indicated in Figure 4.4-2. Estimated capital and operating cost data for these vessels is given in Figure 4.4-3. These figures are derived from several published reports and articles (Voelker et al., 1981a; Global Marine, 1977; National Petroleum Council, 1981; McMullen, 1980) and should be considered preliminary. Capital cost of these vessels is assumed to be amortized over a ten year period.

Vessels used to deliver the supplies and equipment to drilling and production structures in the U.S. Beaufort Sea are required by the Merchant Marine Act, as amended ("Jones Act"), to be built in the U.S., owned by U.S. citizens and operated under U.S. registry. Vessels engaged in icebreaking or ice management only and not carrying cargo to the offshore facilities are not at present covered by this requirement such that Canadian-flag icebreakers have been and are being used for this mission. Legislation (HR6333) was introduced in the 1984 Congress to require the use of U.S. built and U.S. flag ships for that service.

The capital costs presented in Figure 4.4-3 are based on the assumption that these vessels will be constructed in U.S. shipyards. Construction of these specialized ships in a foreign shipyard will result in only slightly lower costs. Operating costs include a 25 man crew, maintenance, insurance, other fixed costs and fuel consumption. In calculating annual operating costs it has been

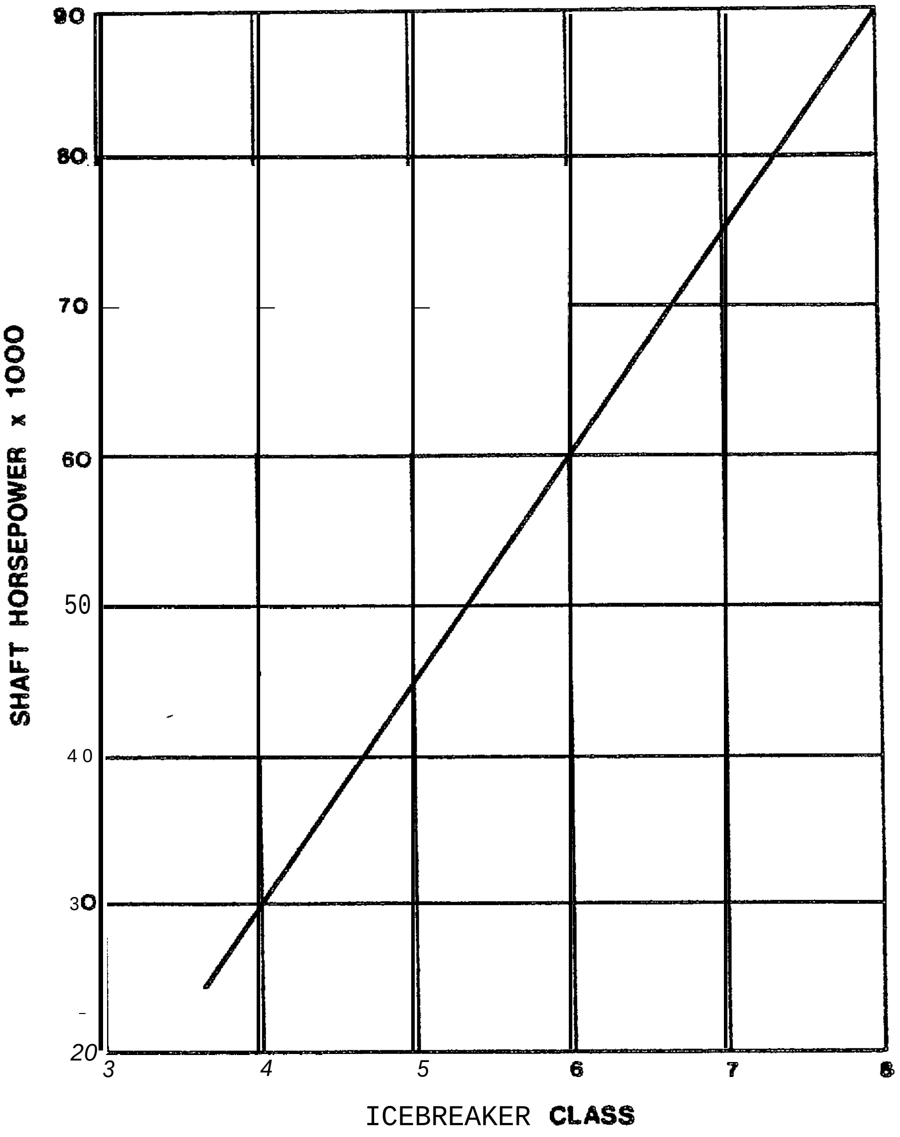

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Figure 4.4-2. Icebreaker shaft horsepower versus Class.

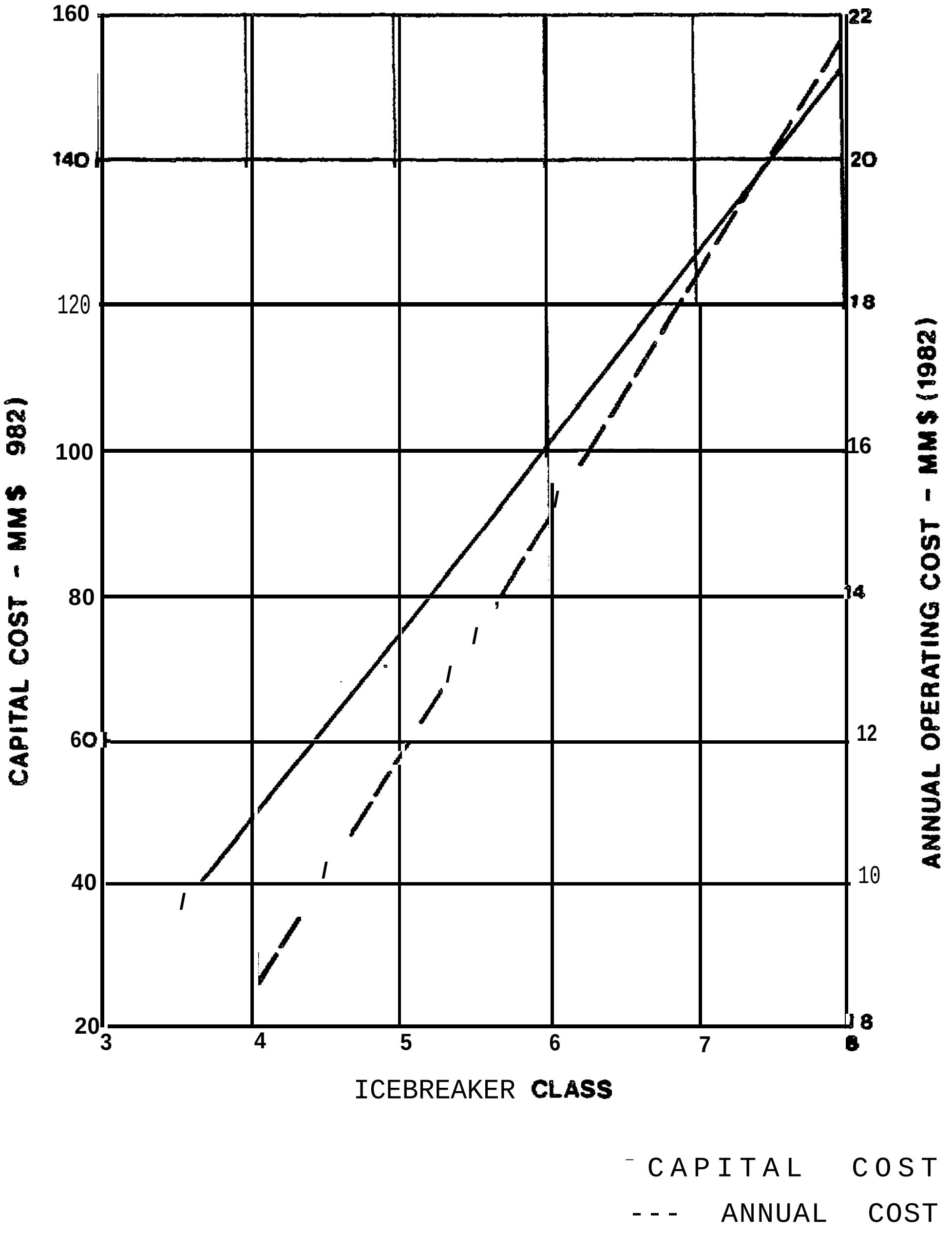

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Figure 4.4-3. Icebreaker capital and annual costs versus Class.

assumed that Class 8 vessels will operate year--round, Class 6 vessels only nine months per year and Class 4 vessels only six months per year. An allowance has been made for lay-up costs during the non-operating periods.

## 4.5 ONSHORE SUPPORT FACILITY TECHNOLOGY, MANPOWER REQUIREMENTS AND COSTS

Offshore operations in the study area will require onshore support facilities. During the construction, exploration and production phases of petroleum development an onshore base camp will be required to provide a staging area for construction equipment, drilling equipment and supplies, and a transfer point for drilling and construction operation personnel. It must include a harbor to receive supplies and serve as the base for the vessels required to support offshore operations, an airstrip for fixed wing aircraft and a helicopter landing area.

The size and features of the base camp, and possibly the need for the camp, will be highly dependent on the location of the offshore operations, the nature of the operations and structures, and the availability of existing infrastructure and base camp facilities. For purposes of this study, it has been assumed that offshore operations will be sufficiently remote from existing infrastructure facilities to require a complete new onshore support facility.

### 4.5.1 Location

The location of the onshore support camp must be selected with care in order to minimize the risk of causing delay to the high cost offshore operations. The first requirement is to be as close as possible to the area of offshore activity. Being close cuts down on the running time required of supply boats and barges and improves the efficiency of helicopter operations. This is especially critical during the seasons of poor weather and ice when the weather window may open only for short periods of time.

An adequate sheltered harbor is required, The harbor must permit the loading and sheltering of supply vessels even though there may be high seas offshore. The harbor must be large enough to allow the maneuvering, anchoring, and berthing of all the supply boats, ocean-going barges, or other vessels supplying the base. Ideally, it should also have the dimensions to accommodate the anchoring and berthing of construction and operation vessels that cannot operate year-round, but this requirement is not essential and the equipment could be laid up for the winter elsewhere. The harbor must be deep enough at quay-side during all tides to take supply boats and ocean-going barges alongside to load or unload the various items of cargo necessary to supply offshore construction, drilling and production operations.

The camp must be connected by road to an airfield with facilities to handle fixed wing passenger and cargo service and an offshore helicopter operation. The principal function of the airfield is to transport crews to and from the offshore facilities. However, the base camp also requires the airfield to permit the rotation of the supply boat crews, to transport emergency supplies and service for personnel via helicopter to offshore locations, to receive emergency supplies for transshipment by supply boats to offshore facilities, to transport sick or injured workers to major medical facilities and to enable a range of administrative and technical personnel from industry and government to have ready access to the camp and the offshore facilities.

### 4.5.2 Facility Requirements

The requirements for the base camp vary as the offshore development progresses from exploration construction through exploration drilling, production construction, development drilling, full production and, eventually, post-production. Therefore," planning must be based on all these phases and the construction of the camp phased to satisfy each phase of the oilfield development. As mentioned above, the characteristics of the camp will depend on many factors. For illustrative purposes, the requirements of a "typical" base camp are developed below. The requirements have been based on the following assumptions:

- Floating construction equipment, such as dredges, self-propelled barges, and tugboats, will be self-supporting, i.e., accommodation and catering for the crew will be on board.
- Construction support equipment has no accommodations and the operating crews, maintenance crews and staff people will be housed in the camp.

- Offshore exploration drilling operations require a total of approximately 95 personnel per platform and only one platform will be in operation.
- Development drilling, utilizing two rigs, requires approximately 140 personnel.
- Full production operations require approximately 190 personnel.
- Large service vessels, such as icebreaker supply vessels, will be self-supporting.
- The camp will be constructed and operated with the minimum facilities required for safety and efficiency.

The following example gives an indication of the base camp requirements for a typical operation to construct a caisson retained island exploration platform and initiate exploration drilling. The main equipment for construction operations will include 2 cutter suction dredges, 7 tugs and 8 dump barges. The manpower required to operate and support this equipment is as follows:

| Equipment | Crew on Board | Crew in Camp |
|---|---|---|
| Cutter Dredges | 2 x 14 = 28 | |
| Tugs 5,000 HP | 7 x8 = 56 | |
| Dump barges | No Crew | |
| Tender tug | 9 | - |
| Crewboat | | 5 |
| Fuel barge | | 1 |
| Survey boat | | 5 |
| Crane barge | | 8 |
| Helicopter | | 3 |
| Bulldozer | | 2 |
| Front end loader | | 2 |

| | | |
|---|---|---|
| Back hoe | | 2 |
| Shore crews | | 12 |
| Warehouse | | 2 |
| Staff | | 10 |
| Camp staff | | 7 |
| Client's personnel | | 5 |
| Maintenance crew | | 3 |
| Total | 93 | 67 |

In addition to the crew involved in the island construction operations there will be a crew on site for the drilling operations. This crew will be housed, during drilling operations, in a mobile camp placed on the island. Prior to operations, a major portion of the crew will be housed in the base camp. This will increase the base camp population by approximately another 70 to 80 people. Therefore, the base camp must initially have sleeping accommodations for approximately 150 people. In addition, the camp will contain:

- messroom and kitchen,
- recreation room,
- first aid room/hospital bed,
- office,
- storage room,
- radio room,
- utility room,
- laundry facilities, and
- bathrooms.

The housing accommodation will have three levels with approximate plan dimensions of 100 x 15 m (330 x 50 ft). Other camp facilities will require approximately the following areas:

| Facility | Approximate Dimensions |
|---|---|
| Airstrip for small aircraft | 1000 x 50 m |
| Helicopter landing area | 50 x 50 m |
| Storage for drill rig | 100 x 150 m |
| Storage for drill pipe, etc. | 100 x 50 m |
| Garage | 20 x 30 m |
| workshop | 20 x 30 m |
| Warehouse | 20 x 30 m |
| Dock area | 100 x 50 m |
| Fuel storage and storage for small marine equipment in winter | 50 x 200 m |

The total required first stage base camp area will thus be approximately 100,000 $m^2$ (1,000,000 $ft^2$). A typical first stage base camp layout is shown in Figure 4.5-1. The base camp may be located onshore or on a reclaimed area, accessible for supply boats and barges with drafts up to approximately 5 m (17 ft). In the event that the facility can be placed onshore, a gravel base will be needed to prevent permafrost from thawing. Approximately 200,000 $m^3$ (260,000 $yd^3$) of gravel would be required to prepare such an area. If the facility is located in an average of 4 m (13 ft) of water, about 800,000 $m^3$ (1,000,000 $yd^3$) of gravel will be needed and all side slopes must be protected against wave erosion.

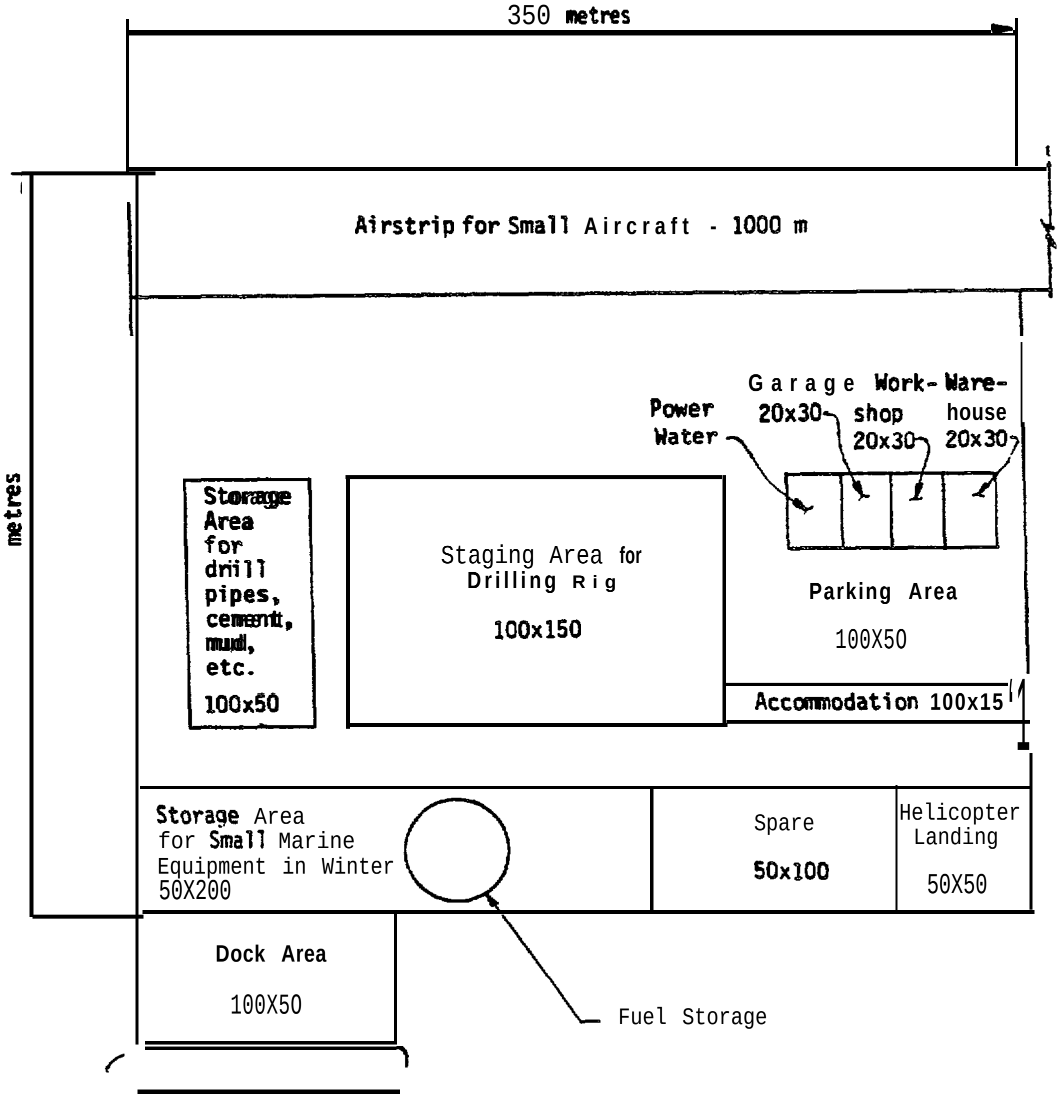

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Figure 4.5-1. First stage base camp layout.

After a commercial discovery is made, the base camp would be expanded to accommodate the increased construction and operation activity associated with offshore crude oil production. As for the first phase of base camp development described above, the requirements for the second phase are highly dependent on the details of the actual production scenario, particularly with regard to type of production platform(s), production rate, type of transportation system and construction/development schedule. More and larger vessels must be accommodated, larger aircraft will be utilized, more personnel will be in transit and more permanent staff will be required. For purposes of this study, it has been assumed that the second phase will double the size and cost of the first phase base camp.

### 4.5.3 Manpower and Costs

The staff required to operate and maintain the first phase base camp numbers approximately 50, including kitchen and housekeeping staff, maintenance crews, helicopter pilots, warehousemen, etc. During the second phase, when the capacity of the camp is doubled, the size of the staff would be increased to approximately 80.

The capital cost of the first phase base camp facilities would be similar to the cost of the facilities for the shallow water artificial islands presently being constructed in the Beaufort Sea. A support camp, as shown in Figure 4.5-1, either onshore or offshore, will probably be built in wintertime, using on-shore gravel sources. The cost of gravel transportation depends on the haul distance and on the cost of building ice roads, if this is required. Onshore and close to the shore, the cost of gravel fill will be \$25 to \$35 per $m^3$ (\$20 to \$25 per $yd^3$) while for distances to the 5 m (17 ft) water depth contour the cost will be \$40 to \$50 per $m^3$ (\$30 to \$40 per $yd^3$), including the cost of ice roads,

The offshore locations must be protected against wave erosion. For temporary use, sandbags are satisfactory, but for structures with a more permanent character, slopes must be protected with concrete blocks, quarry stone or asphalt.

The cost of the gravel fill for a camp as shown in Figure 4.5-1, constructed in an average water depth of 4 m (13 ft), would be:

| | |
|---|---|
| Gravel fill | \$35 MM |
| Permanent slope protection | \$ 5 MM |
| Tots'l | \$40 MM |

The cost of the accommodations, utilities and other facilities and equipment for the first phase camp, including transportation and installation, is approximately \$10 million, making the total capital cost of the camp approximately \$50 million. This cost is assumed to be amortized over a ten year period.

For purposes of this report, it has been assumed that the second phase base camp will cost an additional $50 million.

The annual operating cost of the first phase base camp, including the cost of the camp staff and maintenance of the facilities, is estimated to be approximately $10 million. This cost would be increased to approximately $18 million for the larger second phase camp.

## 5.0 EXPLORATION TECHNOLOGY ASSESSMENT

Exploration in Alaskan Beaufort Sea water depths in excess of 20 m (65 ft) has yet to be carried out although several innovative systems that are capable of operating in depths greater than 20 m (65 ft) have been constructed and are operating in the Canadian Beaufort Sea. A number of concepts have been proposed and there exists no absolute engineering constraint to the development of these concepts. However, the severe environment and relatively deep water poses major engineering problems. The key problem areas can be summarized as:

- Harsh environmental conditions and a very brief open water window for construction.

- Substantial ice impact forces affecting any structure or island concept.

- Poor soil conditions for structure foundation or island construction in many areas.

- Existence of soft overburden which varies substantially in thickness and which could pose significant dredging problems in many areas.

- Unavailability of nearby sources of granular fill and slope protection material in many areas.

## 5.1 EXISTING AND PROPOSED PLATFORM CONCEPTS

Numerous exploration platform concepts have appeared in the literature. These concepts have been developed to differing degrees of refinement ranging from conceptual proposal to full detail design, model testing and, in a few instances prototype construction. It is likely that additional concepts will be developed in the near future. The concepts for which information has been made available are reviewed below. Not all are equally viable and not all are suitable for the water depths considered in this study but they have been included to provide a complete overview. Since there are so many different concepts, the following classification has been established for this study:

- Artificial Islands
- Bottom Founded
- Floating

Some concepts fall within more than one classification and their assignment to a particular classification may be somewhat arbitrary.

The approximate range of environmental conditions in which the various concepts are technically and economically feasible is included with the concept descriptions below. The environmental conditions considered include water depth, seabed material and ice conditions. The data that are provided below are based primarily on published information and the claims of the various concept creators or proponents. No attempt has been made to evaluate these claims or compare the merits of the individual concepts. The order in which the concepts are presented has no significance.

Cost data for existing and proposed exploration platform concepts are not presented. Valid cost information is often difficult to obtain, and even in instances where it is available, sufficient cost basis information (design ice conditions, water depth and seabed soil, equipment included/excluded, fabricated versus installed cost, on-board storage space, number of structure reuses possible, etc.) on which to make meaningful evaluations and comparisons is usually not available. Also, the state of design development, and consequently the reliability of the cost estimates is highly variable among the various concepts as is the method of developing the estimates and the objectives of those preparing them. Therefore, cost data are presented only for the generalized exploration platform concepts described in Section 5.2.

### 5.1.1 Artificial Islands

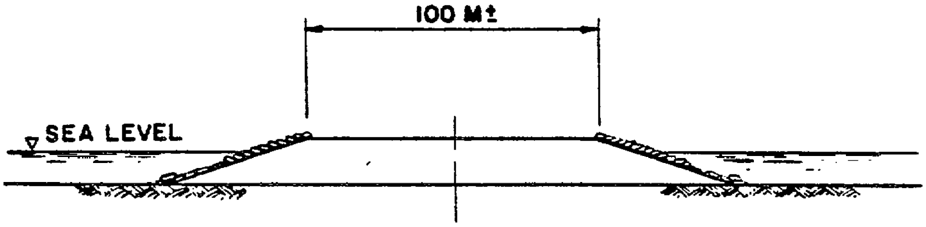
#### Gravel Island

The Gravel Island is the most widely used exploration platform concept in the Alaskan Beaufort Sea. Stability against sliding under ice loads is provided by the shearing resistance of the gravel and the underlying soils. Typically, the gravel is mined onshore and trucked during the winter over ice roads to the construction site.

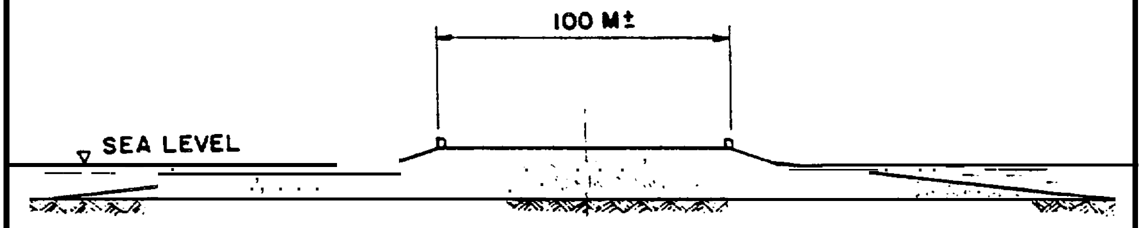
Top diameter of the islands is in the range of 100 to 150 m (350 to 450 ft) and a typical side slope ratio is 1:3. The freeboard depends on water depth and is in the range of 3 to 7 m (10 to 23 ft). Slope protection usually consists of filler cloth covered with gravel filled polypropylene bags. Articulated concrete mats are being considered for slope protection on production islands. Figure 5.1-1(a) illustrates a typical Gravel Island.

Many Gravel Islands have been and are being used, and the concept is being continually developed. They are generally applicable in water depths ranging from 1 to 15 m (3 to 50 ft), although greater depths are possible. The largest Gravel Islands constructed to date are SOHIO's Mukluk in 14.6 m (48 ft) of water and Shell's Seal in 10.7 m "(35 ft) of water. Since the quantity of " gravel required for an island increases exponentially with water depth, the concept usually becomes uneconomical for water depths greater than 15 to 20 m (50 to 65 ft).

Typically, Gravel Islands are designed for 1.8 to 2.2 m (6 to 7 ft) thick first year sheet ice (Ocean Industry, November 1983). The ability to resist the ice force depends entirely upon the shearing strength of the gravel fill and the seabed material. Consequently, a good assessment of the gravel fill and seabed materials and their properties is essential (Kotras et al., 1983).



**(a) CROSS-SECTION OF GRAVEL ISLAND**



(b) CROSS-SECTION OF SACRIFICIAL BEACH SAND ISLAND

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Figure 5.1-1. Gravel and Sand artificial islands.

## Sacrificial Beach Island (SBI)

Sacrificial Beach Islands (SBI) are characterized by long gradual beaches around the drilling surface. These beaches force storm waves to break and dissipate their energy before reaching the island proper. In winter, the sacrificial beach encourages ice sheets to fail in bending and thus form a protective rubble field around the island. Figure 5.1-1(b) illustrates a typical Sacrificial Beach Island.

An SBI is built from sea-bottom material dredged on the site or transported in hopper-dredges. Typically, the dredged material assumes an underwater slope of 1:12 to 1:20 although slopes as steep as 1:5 to 1:7 were achieved using special placement techniques, Typically, the shallow slope results in beach-like conditions, where some of the fill may be washed away by waves or ice errosive action without endangering the overall stability of the island. Secondary slope protection is provided by sandbags and filter cloth on the beach and around the drilling surface.

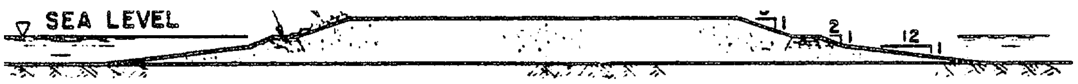
Sacrificial Beach Islands have only been constructed in the Canadian Beaufort Sea. No dredging associated with exploration platform construction has taken place in the Alaskan Beaufort. The technology involved in SBI construction is well established and is being continually improved. The islands are restricted to sites where a sufficient quantity of suitable fill material is locally available for dredging. They have been constructed in water depths up to 20 m (65 ft) and are limited to the landfast and transition ice zones (Dingle, 1982).

### Sandbag-retained Island

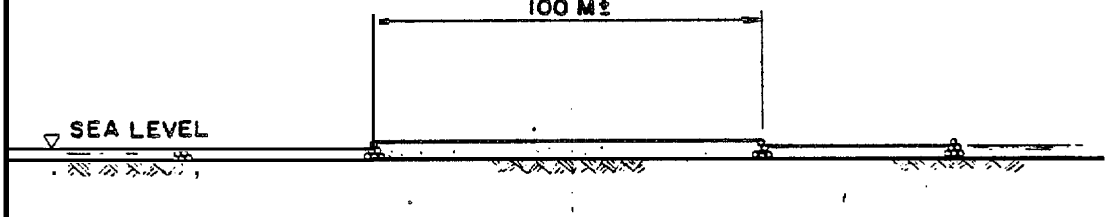
The Sandbag-retained Island is similar to the Sacrificial Beach Island but uses a berm of sandbags to reduce the volume of fill required for construction, as illustrated in Figure 5.1-2(a). This method is attractive in areas where sand is scarce and must be hauled by barge from a remote source. This type of island construction has been confined largely to the shallow waters of the Canadian Beaufort Sea, utilizing summer construction. All have been temporary islands for drilling operations.

A berm of sandbags is placed around the island site and the center area is filled with sand or gravel to the desired elevation. Retention of the lower part of the island by the sandbag berm reduces the required quantity of fill. Side slopes above the berm are protected by sandbags placed on filter cloth. Design criteria include resistance to ice forces, resistance to summer wave erosion, stability of the island fill and seabed foundation, surface area requirements for drilling operations, and quality and availability of fill.

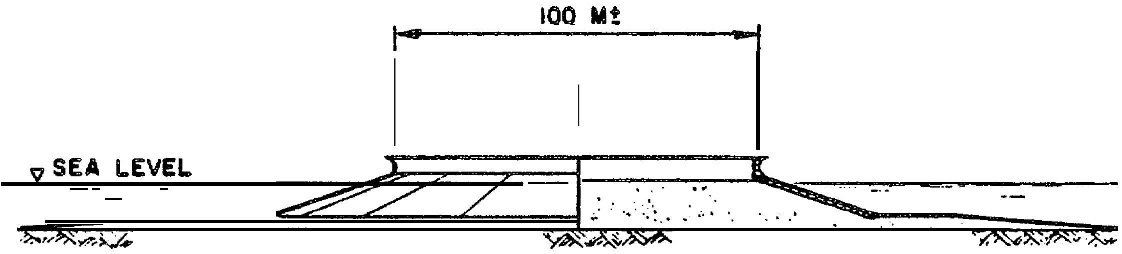
This technology has been used effectively to build at least seven islands. The water depth for which it has been found suitable



(a) **CROSS-SECTION OF SANDBAG-RETAINED ISLAND**



**(b) CROSS-SECTION OF SANDTUBE-RETAINED ISLAND**



(c) **CROSS-SECTION OF NECKLACE ISLAND**

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Figure 5.1-2. Sandbag-retained, Sandtube-retained and Necklace artificial islands.

ranges from 2 to 7 m (6 to 23 ft) and it is applicable strictly in the landfast ice zone (Dingle, 1982).

### Sandtube-retained Island

Sandtube-retained Islands are similar to Sandbag-retained Islands and have potential use in the shallow waters of the Beaufort Sea in depths up to approximately 3 m (10 ft). In this type of exploration island, as illustrated in Figure 5.1-2(b), sandtubes are laid in a circular pattern to form a retaining wall and dredged material is pumped into the center until the proper elevation is reached. Construction is performed during the summer. One variation on this concept would be to build a protective berm around the required drilling area by pumping fill into the annulus between two concentric rings of sandtubes. Ice would run up the sloping outer face of the island and then pile up between the two rings.

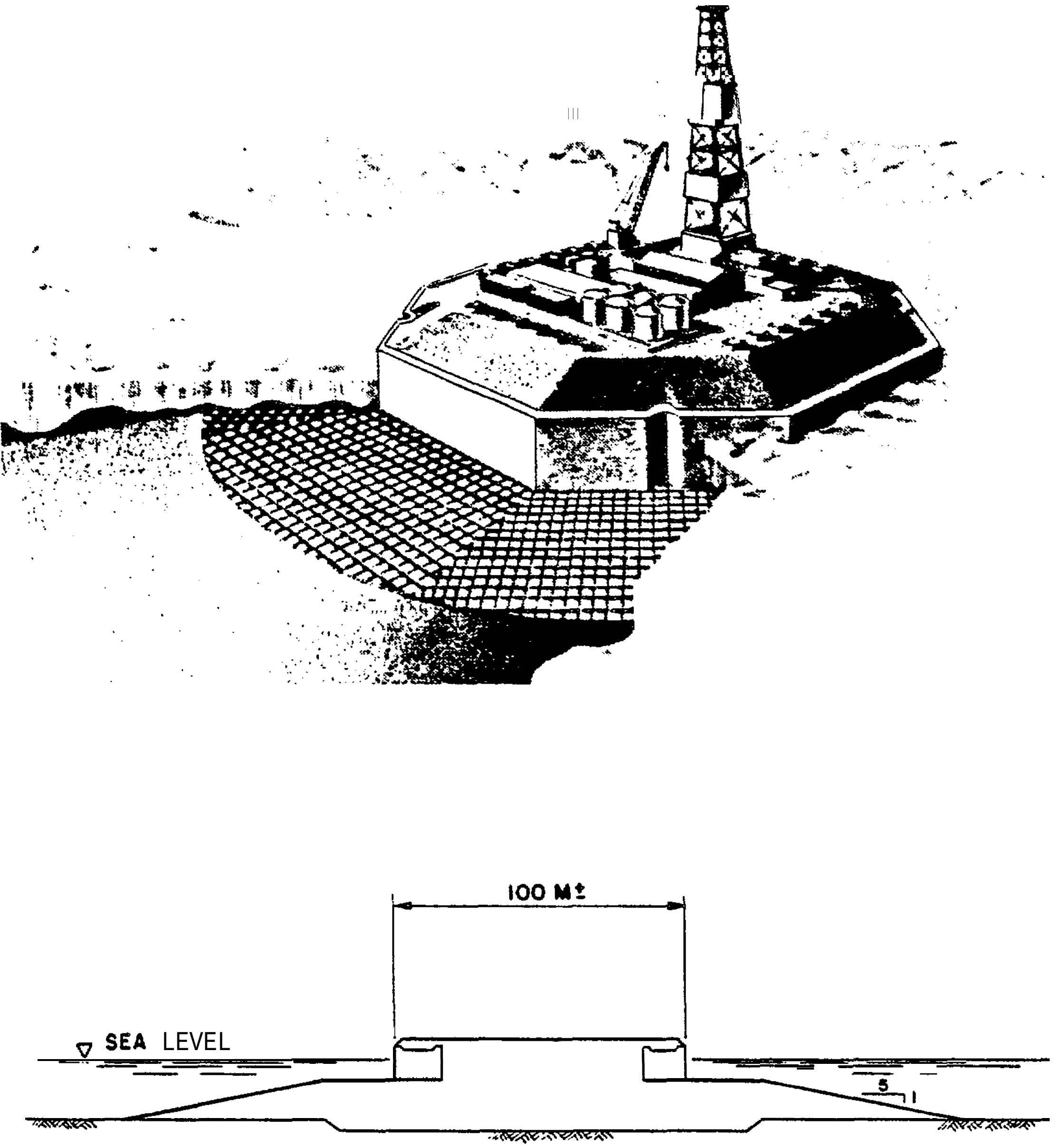
This concept is in the proposal phase and the system is under test (Offshore Engineer, September 1982 ).

### Necklace

Necklace is in the conceptual design stage. As illustrated in Figure 5.1-2(c), it is a movable retained island and is designed for a 2.2 m (7 ft) thick sheet of ice. It is intended for use in a maximum water depth of 18 m (60 ft). The concept consists of a series of trapezoidal steel elements strung together to form a truncated cone. In deeper water, a prepared pad is required to provide the maximum 8 m (25 ft) depth for set-down. The elements are towed to the site in single or twin groups connected by chains or wire ropes. At the site, the innermost (upper) connecting chains or ropes would be tensioned to form a ring. The elements would then be ballasted by flooding of tanks in the outer ends, while the lower connecting chains are tensioned to form the completed truncated cone. After final ballasting the ring is filled with dredged sand. The ring can be refloated by releasing tension in the chains and by deballasting the units. (Offshore Petroleum: A Business Opportunities Program, April 1981).

### Tarsiut Caisson Island

Tarsiut Island was constructed in the Canadian Beaufort Sea a water depth of 21 m (70 ft) in 1981. It has the advantages over unretained artificial islands of not being limited to relatively shallow water, due to lesser requirements for fill volume, and of being less susceptible to summer storms. Tarsiut Island was built utilizing four reinforced concrete caissons installed on a submerged berm with a 1:5 slope, as Illustrated in Figure 5.1-3. The caissons were built in a graving dock in Vancouver, B.C., and towed to the Arctic on a barge. They were joined together with steel gates and all the cells were filled with sand. The caissons are free to move relative to each other so that the ice forces are transferred into



CROSS-SECTION

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Figure 5.1-3. **Tarsiut** Caisson Island.

the island fill material. The island required one construction season to complete, as opposed to the two seasons required for the deepest sand or gravel islands.

The caissons, which are designed to be removable and to be used at least twice, are capable of resisting annual ice and multiyear ice forces of 4,100 kPa (600 psi) over a 2 x 2 m (7 x 7 ft) square. However, they are not designed for a major polar ice pack invasion. Tarsiut Island is also designed for installation in a 1 m significant sea. However, it did sustain some wave damage during installation (Fitzpatrick and Stenning, 1983).

## Caisson Retained Island (CRI)

The Caisson Retained Island, illustrated in Figure 5.1-4, was first deployed in the Canadian Beaufort Sea in the summer of 1983 and redeployed in the summer of 1984. The justification of the CRI over an artificial island becomes evident in deeper water depths or where abundant borrow material is not available. The CRI consists of eight trapezoidally shaped caissons, tied in a ring by two sets of eight cables. At locations deeper than 9 m (30 ft) it is necessary to build an underwater berm to an elevation 9 m (30 ft) below sea level. The caisson ring is filled with dredged material but it could be moved each season. As with Tarsiut Island, flexible joints permit the caissons to move relative to the shape of the frozen plug of fill material and thus transfer the ice loading into the core.

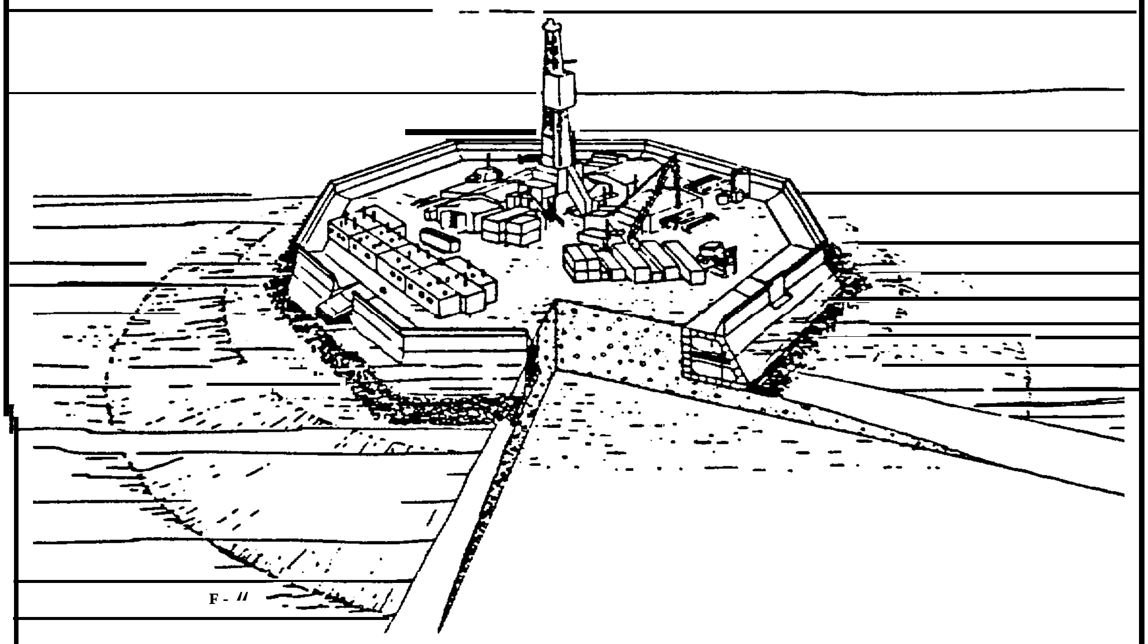

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Figure 5.1-4. Caisson Retained Island (CRI).

The existing CRI has a set down depth of 9 m (30 ft) and has been installed in water depths of 18 m (60 ft) and 26 m (86 ft). It was designed for use in the landfast ice zone. The caissons are portable and are intended to be reused at least four times (Mancini et al., 1983; de Jong and Bruce, 1978).

While the existing CRI is designed for a maximum water depth of 18 m (60 ft), the basic concept is applicable to much deeper water. The selection of the optimum height of the caissons and the berm for any particular water depth would be based on an economic evaluation of the various alternatives.

### Stacked Steel Caisson System

The Stacked Steel Caisson System, as illustrated in Figure 5.1-5, is a relocatable retained island suitable for 4 to 20 m (13 to 65 ft) of water. It is only in the conceptual design stage. The system consists of an octagonal, self-contained upper drilling barge, a mid-caisson and a base caisson. The system may be installed on a sand berm. The basic idea is to provide versatility and to use as many sections as required by the water depth at the site.

The upper barge serves alone in shallow water depths. The mid-caisson extends the water depth to 12 m (40 ft), and the base caisson brings it to 20 m (65 ft). The inner core of the caissons is filled

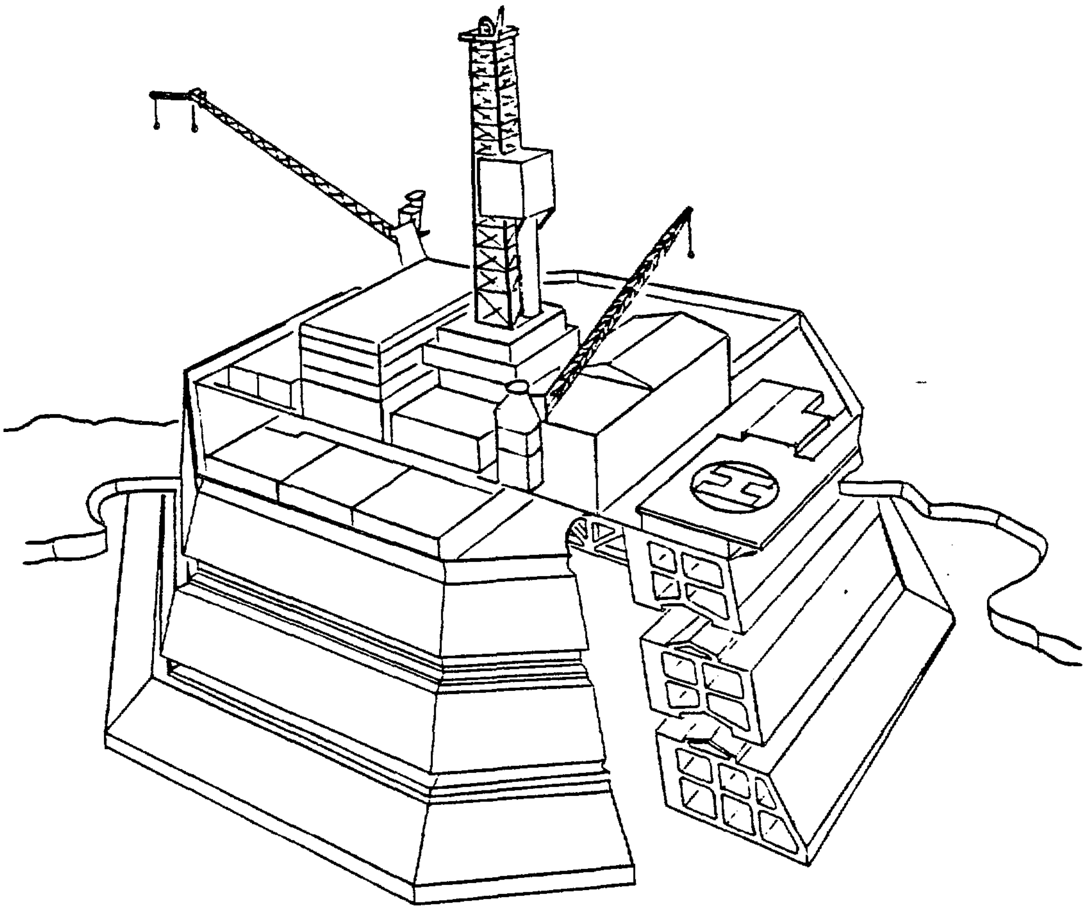

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Figure 5.1-5. Stacked Steel Caisson System.

with sand. The base caisson is 131 m (430 ft) wide (Offshore Engineer, January 1983).

## Cellular Island

The Cellular Island is a retained artificial island type exploration structure, as illustrated in Figure 5.1-6. It has the advantage of requiring less fill than typical gravel or sacrificial beach islands. The proposed concept comprises 23 m (70 ft) diameter cells constructed of interlocking sheet piling arranged in a circle of the required diameter, generally between 100 and 150 m (300 and 450 ft). The circumferential cells are circled by a tied-back sheet pile bulkhead and the entire structure is filled with sand or gravel. The "cellS-in-a-cell" configuration presents a smooth surface to pack ice and induces buckling failure of the ice. The mass of frozen soil fill resists the ice forces and the entire island is frozen into the seabed.

Construction of islands in excess of 100 m (330 ft) in diameter in water up to 15 m (50 ft) deep can be accomplished in 60 to 90 days. In waters up to 13 m (43 ft) deep, piling would be driven directly into the seabed; for greater depths, up to 30 m (100 ft) at high tide, a submerged berm would be constructed as a base for the cellular islands.

The platform is in the conceptual design stage. The design was

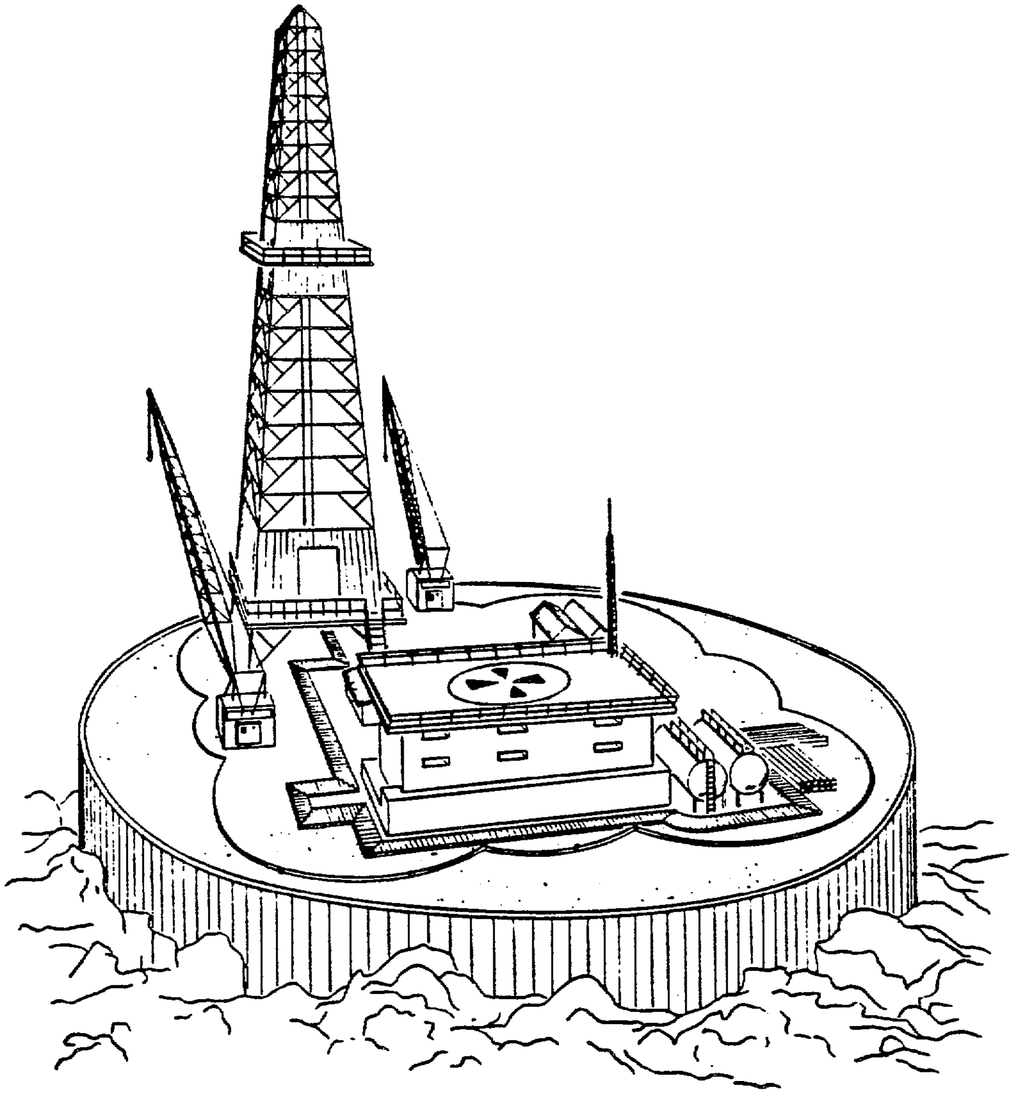

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Figure 5.1-6. **Cellular** Island.

developed for 13 m (4 ft) of water, but as mentioned above, the concept can be applied in water depths up to 30 m (100 ft) (Forsenn, 1978).

## Summary

A summary of the various Artificial Island exploration platform concepts is presented in Table 5.1-1.

TABLE 5.1-1

SUMMARY OF ARTIFICIAL ISLAND EXPLORATION PLATFORMS

| CONCEPT NAME | FIG. NO. | MAXIMUM WATER DEPTH (m) | PRESENT STATUS |
|---|---|---|---|
| Gravel Island | 5.1-1(a) | 20 | Operational |
| Sacrificial Beach Island (SBI) | 5.1-1(b) | 20 | Operational |
| Sandbag-retained Island | 5.1-2(a) | 7 | Operational |
| Sandtube-retained Island | 5.1-2(b) | 3 | Proposed |
| Necklace Island | 5.1-2(C) | 18 | Proposed |
| Tarsuit Caisson Island | 5.1-3 | 21 | Operational |
| Caisson Retained Island (CRI) | 5.1-4 | 26 | Operational |
| Stacked Steel Caisson System | 5.1-5 | 20 | Proposed |
| Cellular Island | 5.1-6 | 30 | Proposed |

### 5.1.2 Bottom Founded Concepts

#### Arctic Cone Exploration Structure (ACES)

The Arctic Cone Exploration Structure (ACES) is the result of a development program which began in 1981 to design a mobile drilling unit which could operate beyond the 15 m (50 ft) depth contour in the most exposed ice conditions. ACES is comprised of a cone, surmounted by a short cylinder, which in turn supports an enclosed drilling facility, as illustrated in Figure 5.1-7. The cone and cylinder are lightweight prestressed concrete while the superstructure is steel. The cone is sized to meet several requirements: to produce bending failure of multiyear ice features, to provide adequate contact area with the sea floor, and to provide sufficient buoyancy during tow and installation.

At present, a design has been developed which provides drilling capabilities for the water depth range of 15 to 33 m (50 to 110 ft). However, the general concept is suitable for deeper water depths. Although the preliminary design is complete, the design criteria are still under review and subject to change as more information becomes available about the environment and conditions in the operating area.

ACES is designed for year-round operations in exposed offshore areas of the Arctic and is equipped to drill three wells without resupply. It is capable of operating on a wide range of bottom

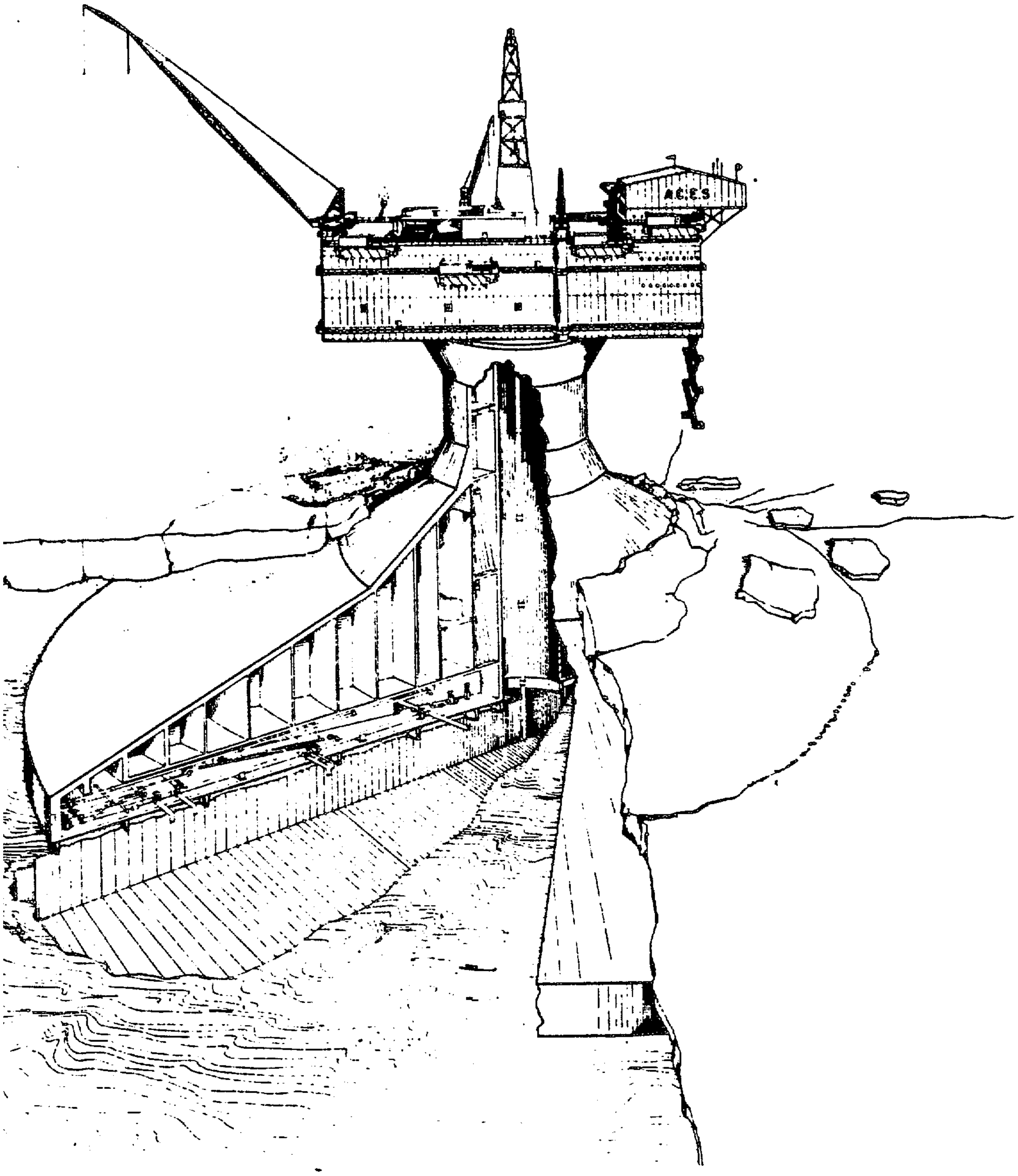

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Figure 5.1-7. Arctic Cone Exploration Structure (ACES).

conditions, with the critical seabed soil profile which dominated the foundation design consisting of 15 m (50 ft) of clayey silt underlain by dense Pleistocene sand or bonded permafrost.

The drilling unit has been designed to withstand without damage significant wave heights of 6.7 m (22 ft) and 10 m (33 ft) in 15 m (50 ft ) and 30 m (100 ft ) water depths, respectively, and maximum sustained wind velocities (1 minute) of 180 km per hr (98 knots). In designing ACES for ice loads, the two critical loading conditions were found to be pressure ridges with an attached multiyear floe and adfreeze bonded sheet ice. The ridges were considered to have a fully consolidated core extending to a maximum depth of 20 m (65 ft) below the waterline or the water depth minus 3 m (10 ft), whichever is less (Byrd et al., 1984).

### Mobile Arctic Caisson (MAC)

The Mobile Arctic Caisson (MAC), illustrated in Figure 5.1-8, is a bottom founded structure which has the capability of year-round operation in a variety of ice conditions, including 5 to 8 m (17 to 27 ft) ice floes and ridges up to 21 m (70 ft) consolidated thickness. MAC, which was deployed in the Canadian Beaufort Sea in the summer of 1984, is capable of operating in water depths of 15 to 40 m (50 to 130 ft).

MAC is a “deep” steel caisson, which in effect replaces the top

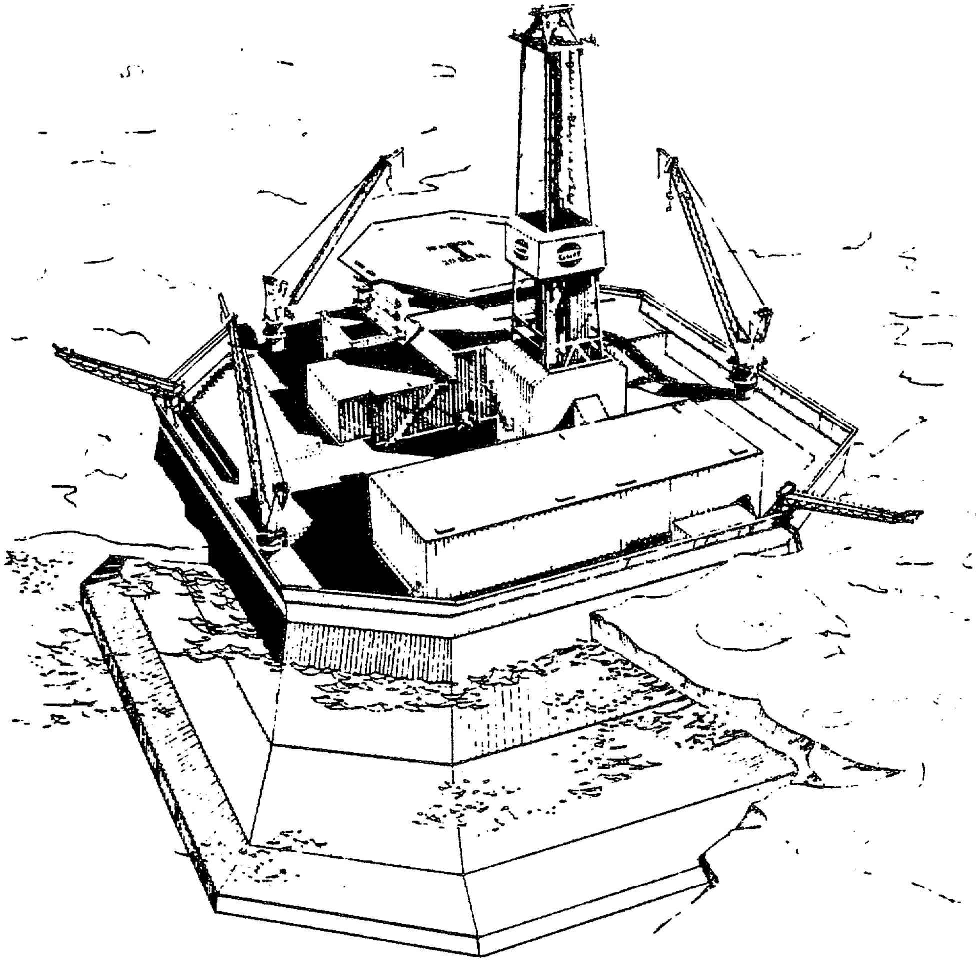

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Figure 5.1-8. Mobile Arctic Caisson (MAC).

21 m (70 ft) of a gravel or sand artificial island. It is essentially a continuous steel ring, the core of which is filled with sandto provide most of the resistance to ice loads. The deck is a bridge-type structure supported by inner walls. The caisson can be relocated annually. Set-down and refloating is achieved by the addition or removal of water ballast. Insulation is provided on critical areas of the caisson and heat is supplied both in and under the deck as well as to the ballast tanks to prevent freezing. If a berm is required, it would be prepared a year in advance of the caisson set-down. MAC has sufficient storage capacity to drill two wells with limited resupply (Bruce and Barrington, 1982; Stewart et al. 1983).

MAC is designed for a specific set-down depth, but the basic concept is applicable to a wide range of water depths. By varying the heights of the structure and berm, the economic optimum combination can be determined based on evaluation of availability of fill material, cost of the structure, possible reuse requirements, seabed conditions and other factors.

### Arctic Mobile Drilling Structure (AMDS)

The Arctic Mobile Drilling Structure (AMDS) is intended for use in the land-fast zone of the Beaufort Sea in 6 to 18 m (20 to 60 ft) of water. It is capable of drilling two or three wells per location but only one well without resupply. As illustrated in Figure 5.1-9,

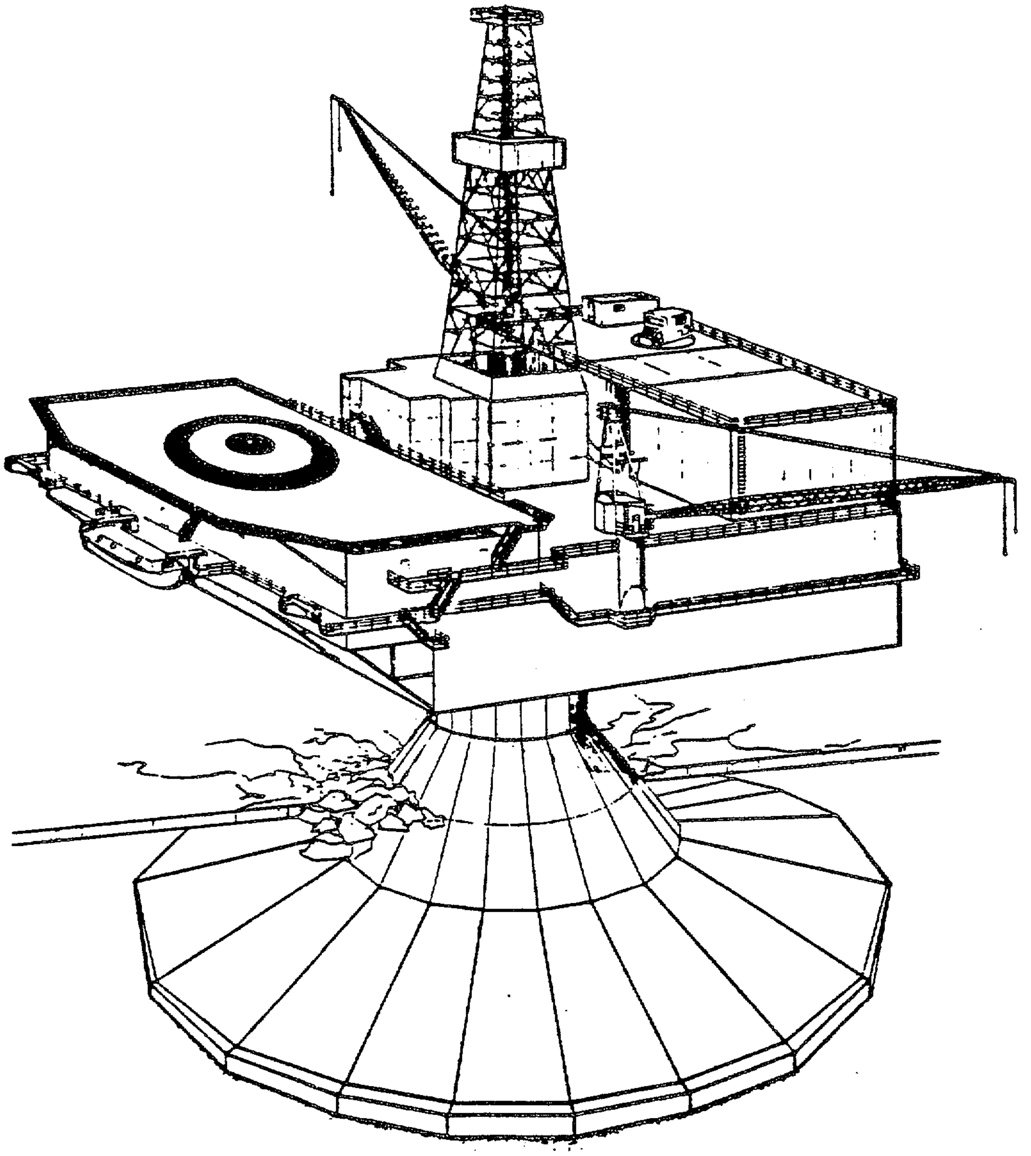

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Figure 5.1-9. Arctic Mobile Drilling Structure (AMDS .

the steel structural base is of a faceted conical shape. The sloping conical surface causes ice to ride up and break in flexure and is heated by a hot water system to prevent adfreeze. The upper cone and column are heated by electrical resistance panels. A shallow skirt is provided around the base and ballasting is by sea water.

The design is in the conceptual stage. The potential variability of ice loads justifies further research in this area. Another area which requires further attention is the selection of the hull configuration in order to clear broken ice pieces.

AMDS has been designed to resist first-year. sheet ice containing multiyear ice pieces. The heated, sloped side technology which minimizes ice loads, has potential application for production structures as well as drilling structures. In addition, the concept could be extended to water depths greater than the 18 m (60 ft) limit of the present design (Hancock et al., 1979).

### Mobile Gravity Platform (Monotone)

The Mobile Gravity Platform or Monotone, illustrated in Figure 5.1-10, is designed to operate year-round without resupply as a bottom founded drilling platform in water depths ranging from 10 to 41 m (33 to 135 ft). It is thus capable of resisting multiyear ice loads. The Monotone contains a conical steel collar which can be moved up and down on the cylindrical prestressed concrete shaft and

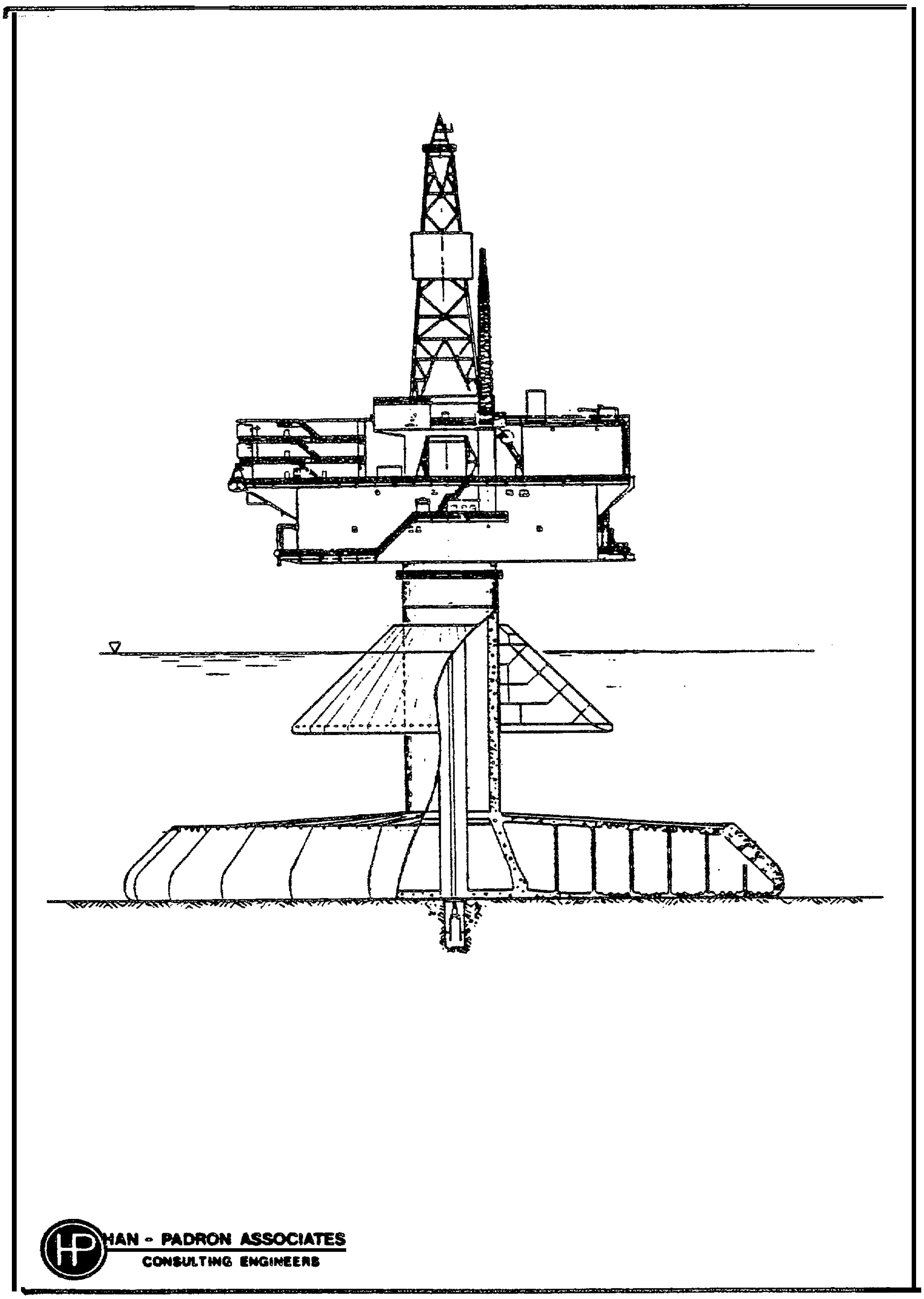

**Figure 5.1-10.** Mobile **Gravity** Platform **(Monocone)**.

frictionally clamped at the desired level to cause the ice to ride up (or down, if the cone is inverted) and fail in flexure. The collar is heated to prevent adfreeze. The lower hull is made of prestressed concrete and is used to float the structure to the site. It is then ballasted down to bear on the seabed. The rectangular steel superstructure includes three decks which house the drilling system, dry bulk and pipe storage, mechanical systems, power generation and crew quarters.

The Monotone is in the preliminary design stage. Although the present design has a 41 m (135 ft) maximum operating depth constraint, the concept of a movable conical collar has potential applications for deeper water depths as well. Its minimum operating depth is limited by its light ship draft. For water depths of less than 17 m (56 ft) the structure must be placed in a dredged hole.

The structure is designed to rest on a 0.6 m (2 ft) thick sand blanket which provides sliding resistance. In order to insure operability over a wide range of soil conditions, both cohesive and cohesionless soils, with an ultimate shear strength of 21 kPa (440 psf) and a friction angle of 30°, respectively, were considered in the design (Jazrawi and Khannan, 1977).

### Monopod Jack-up Drilling Rig

The Monopod Jack-up Drilling Rig, illustrated in Figure 5.1-11,

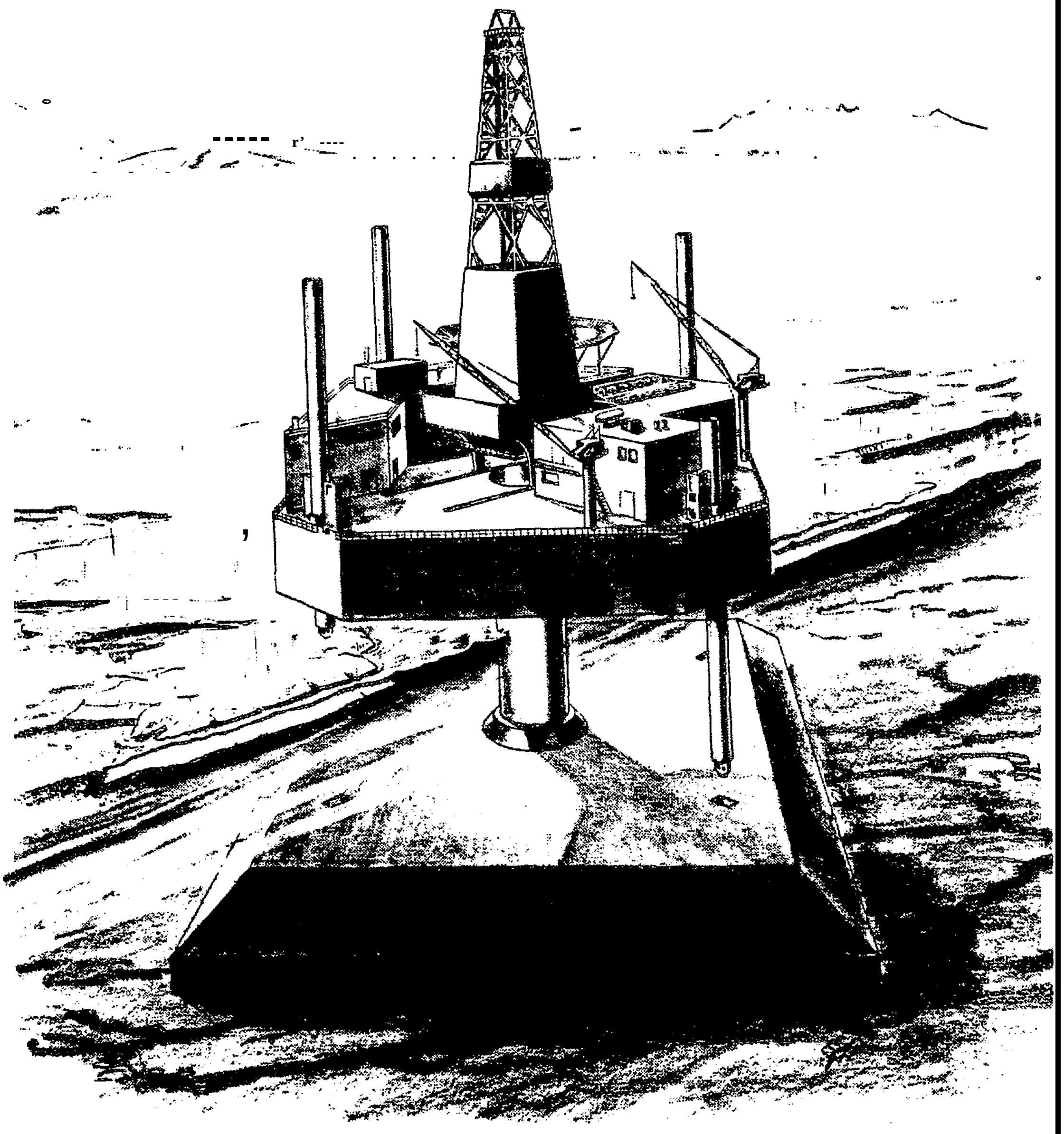

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Figure 5.1-11. Monopod Jack-up Drilling Rig.

is designed to operate in water depths ranging from 11 to 27 m (37 to 90 ft) in the Arctic offshore environment. It has sufficient capacity for enough supplies to permit up to four months of continuous operation. Its chief advantages are:

- drilling efficiency of a conventional jack-up rig,
- fixed monopod center column to minimize the effects of high ice loads, and
- mobility of a simple gravity structure.

Detail design of the Monopod Jack--up concept is complete for application in water depths up to 60 m (200 ft). The rig is designed to operate in a wide range of soil conditions, with a minimum friction angle of 33°, and, minimum cohesion of 48 kPa (1,000 psf). The ice conditions result in the governing environmental design loads. Local ice pressures of as high as 17 mPa (2,500 psi) over a 10 x 90 cm (4 x 36 in. ) area, and multiyear ice floes of 600 m (2,000 ft) diameter and 7.5 m (25 ft) thickness with a summer velocity of 1 m per sec (3 ft per see) were considered in the design (Offshore, December 1982).

On location, the Monopod Jack-up rests on a rectangular base with sloping sides and a steel column extends above the base to support a deck. The base uses saltwater ballast to resist the overturning moment from ice forces and unbalanced gravity loads. For installation, the base is ballasted until the rig floats *on* the platform hull, then the base is lowered to the seabed using four jacking legs. The jacking legs raise the platform to the top of the center column and the platform is secured to the column. The jacking legs are then hydraulically released from the base and raised clear of the ice.

### Mobile Arctic Drilling Structure (MADS)

The Mobile Arctic Drilling Structure (MADS), illustrated in Figure 5.1-12, is a sloping sided, steel, gravity structure capable of operating in water depths ranging from 4.5 to 12 m (15 to 40 ft). MADS was designed as a cost-effective alternative to the gravel island for those operators interested in a sustained, multiyear drilling program, or those who do not have suitable gravel sources. As with other bottom founded structures, it becomes more cost-effective in deeper waters. MADS is in the conceptual design stage. It is composed of three main sub-elements, the ballast hull, the pontoons and the platform deck, The ballast hull is a lightly framed structure forming the central core of the unit and is primarily designed for containment of the seawater ballast. The sloping sided pontoons are also compartmentalized for seawater ballast. They are heavily framed structures that interface with the ice and which are structurally integrated with the ballast hull. The platform deck section supports the drilling rig and quarters and contains storage space for drilling consumables.

The unit is designed for operation on all types of seabed soil,

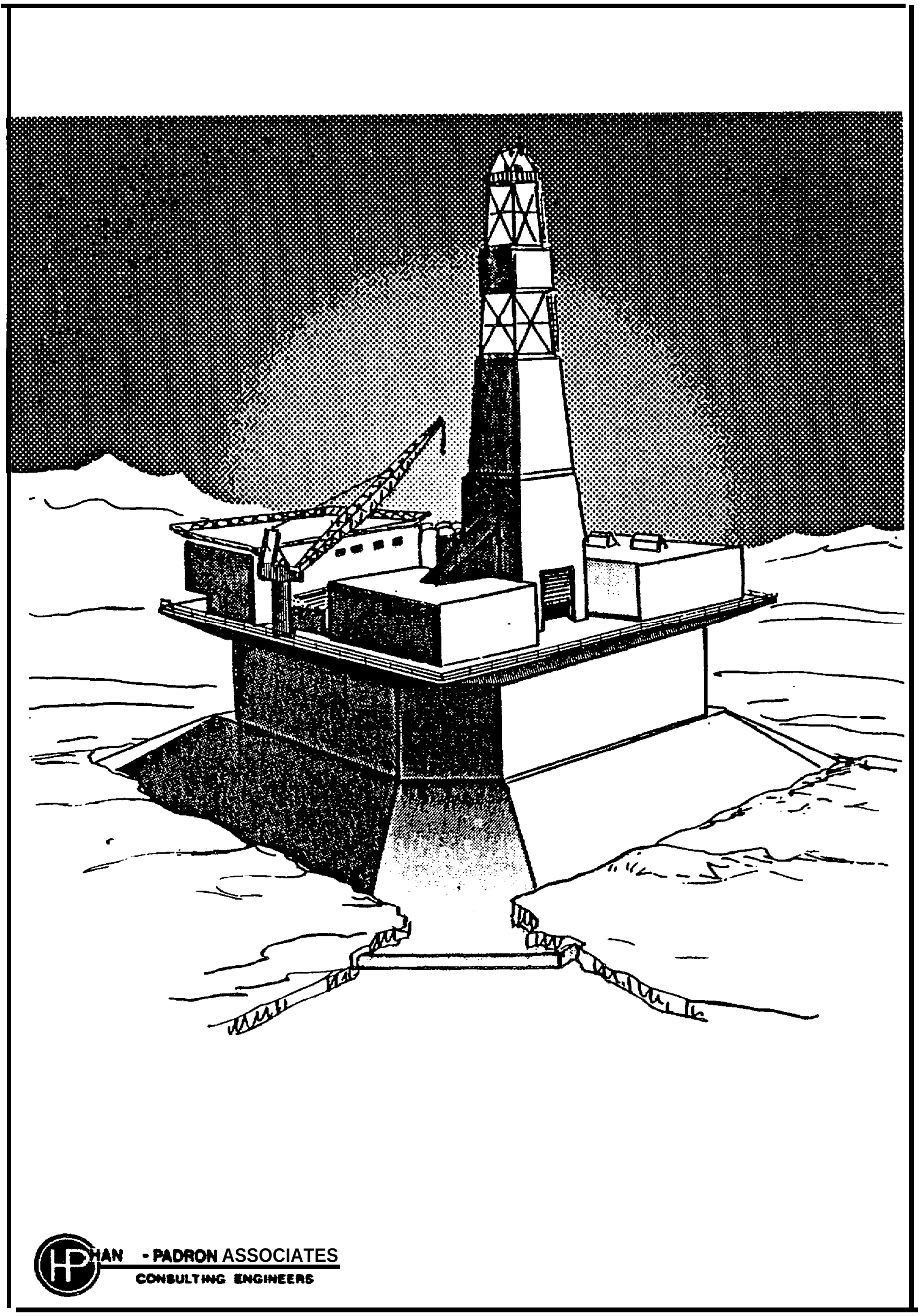

Figure 5.1-12. Mobile Arctic Drilling Structure (MADS).

as the sloping sides minimize the ice loads. It is suitable for deployment in the land fast ice zone and can be mobilized for relocation by simply pumping out the salt water ballast. MADS has storage capacity for drilling up to three wells over a ten month period without resupply (Wetmore, 1984b).

### Sohio Arctic Mobile Structure (SAMS)

The Sohio Arctic Mobile Structure (SAMS) is a bottom founded, movable drilling platform which is capable of operating in 12 to 18 m (40 to 60 ft) of water. However, the basic concept has potential applicability to any movable gravity-based or caisson type structures in the Beaufort Sea which are subject to high lateral loads. As illustrated in Figure 5.1-13, SAMS is an octagonal, water-ballasted, prestressed concrete structure, with its unique feature being the use of foundation "spuds," or short stubby piles, to increase resistance to sliding. The spuds are driven only deep enough to accomplish shear transfer and are not designed for vertical loads (free movement in the vertical direction is unrestricted). The base slab and upper slab are reinforced by steel assemblies to accommodate concentrated loads. A particularly attractive feature of the spud concept is the ability to vary the number of spuds as required by soil or ice conditions. Wells are protected in caissons below the platform base.

The soil profile used in the design consists of 9 m (30 ft) of soft silts and clays overlying strong Pleistocene sands. However,

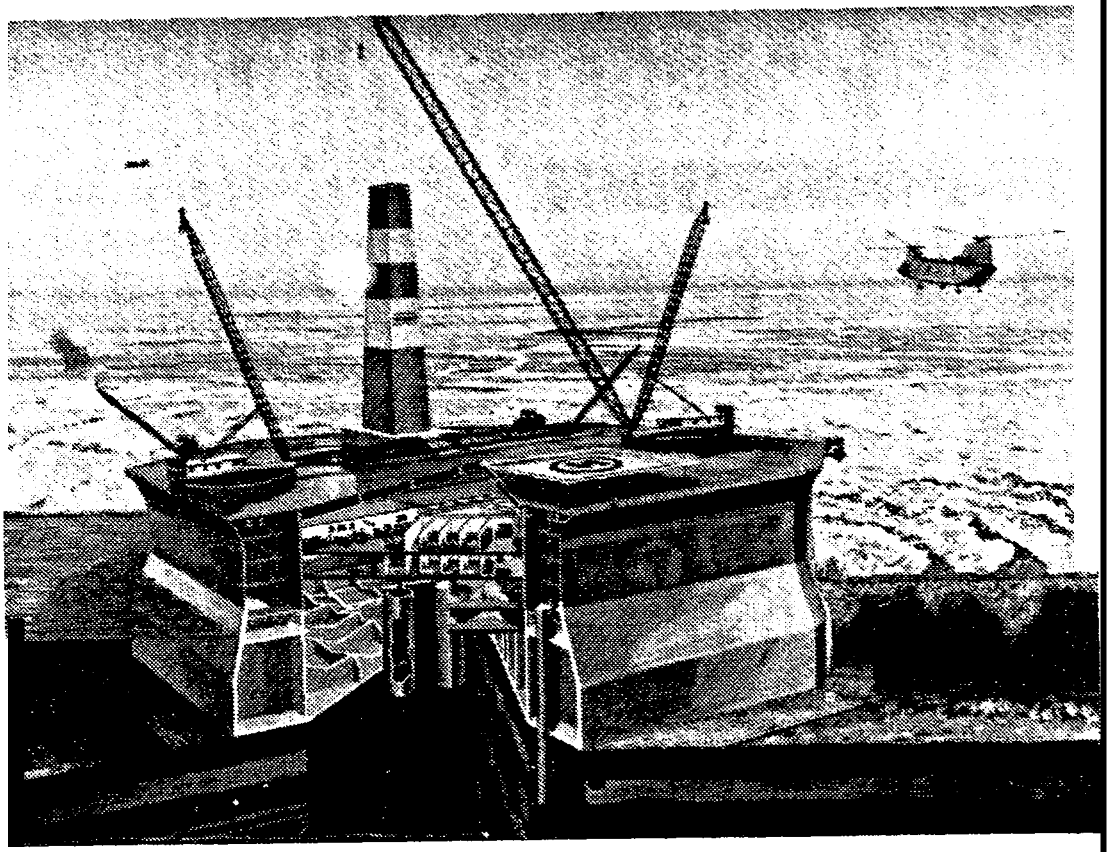

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Figure 5.1-13. **Sohio** Arctic Mobile Structure **(SAMS).**

the basic concept is applicable to varying soil conditions (Gerwick et al., 1983; Bea, et al., 1984). At the present time, a detail design has been developed but construction has been cancelled.

### Concrete Island Drilling System (CIDS)

The Concrete Island Drilling System (CIDS), illustrated in Figure 5.1-14, is a mobile, modular, stackable, gravity drilling platform for year-round use in the Beaufort Sea. As presently designed it is suitable for exploration drilling of up to three wells per year without resupply. It represents the first Arctic use of a completely self-contained mobile offshore drilling unit which does not rely on use of dredge support operations for either bottom preparation or ballasting. CIDS is made up of a steel mud base and a concrete center module topped with two steel drilling barges, side by side. The overall depth can be varied by using one or two concrete center modules. Each concrete module contains interconnected vertical precast silos between top and bottom slabs. Utilizing seawater ballast, the unit can be refloated and moved intact to a new configuration.

The system, which has an operating depth of 10.5 mto 17 m (35 to 55 ft) of water, has been deployed west of Harrison Bay off Pitt Point, and drilling of the first well commenced in the Fall of 1984. The concept has potential applicability for up to 30 m (100 ft) of water, and for production structures as well. The unit. that has been

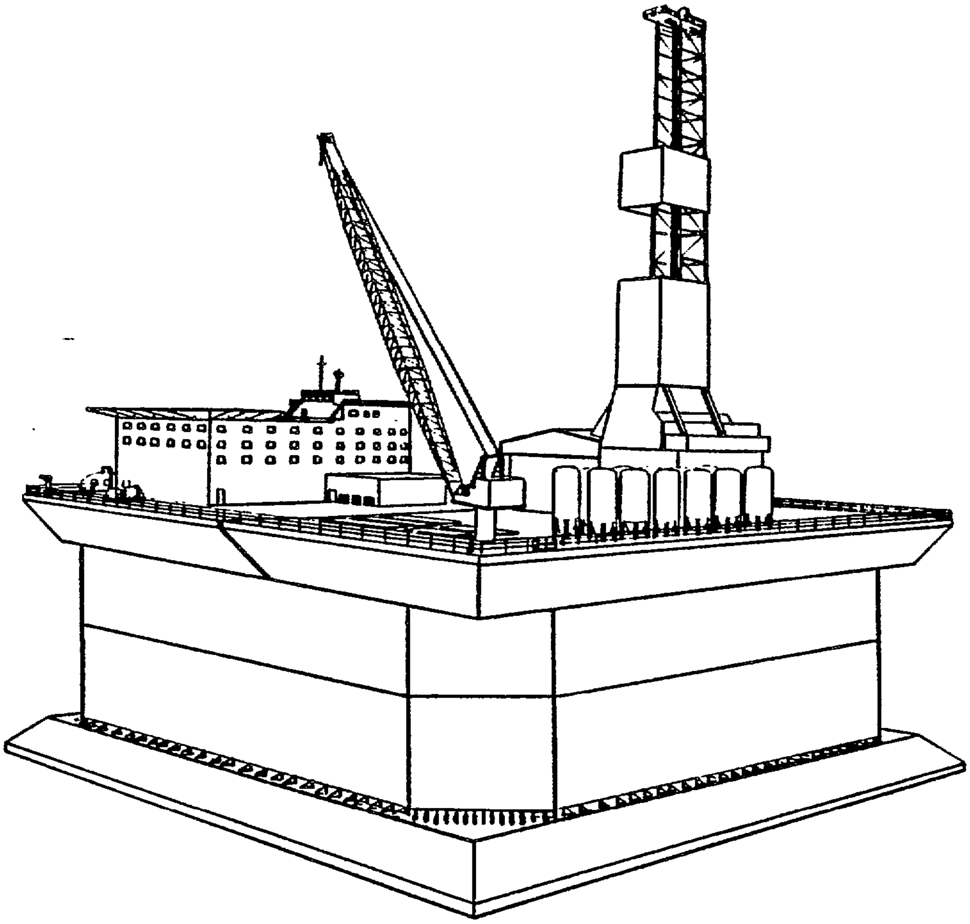

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Figure 5.1-14. Concrete Island Drilling System (CIDS).

deployed was designed using a soil shear strength of 96 kPa (2,000 psf), and the option of a mud base was used to increase the base area. For cohesionless soil, a mud base would not be necessary. Some method of soil strengthening may be necessary if the structure were to be deployed on a weaker bearing stratum.

In the design against ice loads, 2 m (7 ft) thick first-year ice, up to 6 m (20 ft) thick multiyear ice floes, 2.7 m (12 ft) thick consolidated rubble, and three 1.5 m (5 ft) sheets of rafted ice, were considered. In addition, CIDS employs an ice monitoring system and protective spray ice barrier which further adds conservatism to its operations (Wetmore, 1984a; Offshore, 1982; Ramsden, 1984).

### BWA Caisson System (BWACS)

The BWA Caisson System (BWACS) is a movable, bottom mounted gravity exploration platform system, as illustrated in Figure 5.1-15. The present design is capable of accommodating nine months of supplies, and three wells of 5,000 m (16,000 ft) can be drilled from a single location. BWACS is constructed of lightweight prestressed concrete and relies solely on water ballast for stability in place. Structurally, the platform is a box of vertical hexagonal cells with continuous top and bottom slabs. A wide range of sites is acceptable, since site preparation is limited to the placement of a thin sand pad. Artificial drains, such as sand drains or sand wicks, can be installed from within the structure to make use of the

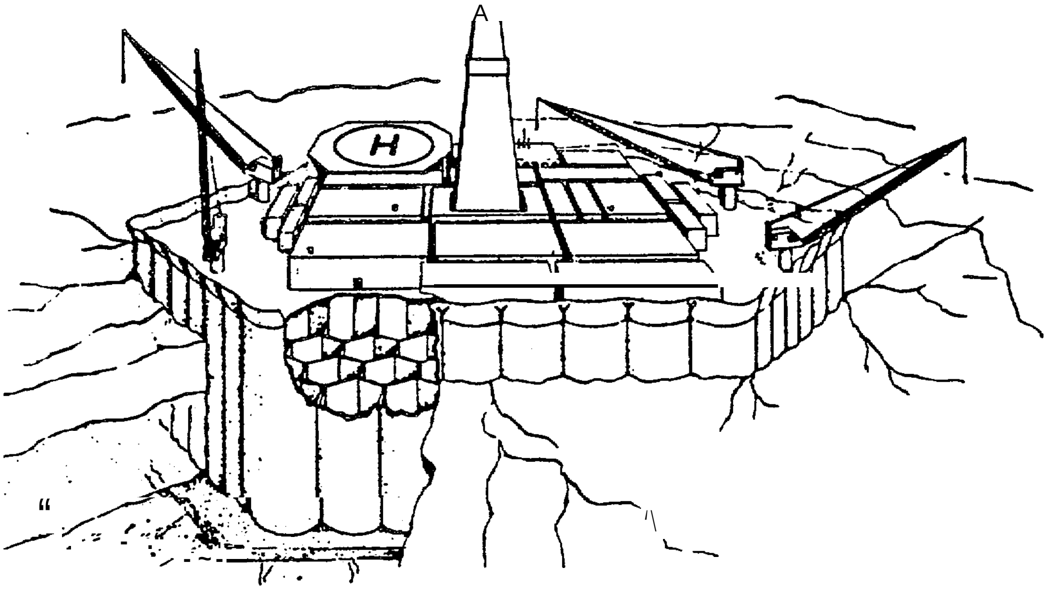

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Figure 5.1-15. BWA Caisson System (BWACS).

strength gain in the foundation soils produced by the structure weight.

The preliminary design of the structure is complete. The system is suitable for water depths of 9 to 18 m (30 to 60 ft) in the land fast ice zones of the Beaufort Sea. It has been designed for 2 m (6 ft) of sheet ice and 5 m (17 ft) of consolidated rubble piles (Bhula et al., 1984).

## Single Steel Drilling Caisson (SSDC)

The Single Steel Drilling Caisson (SSDC), also referred to as the Semi-submersible Drilling Caisson, is a drilling unit able to work year-round in the Arctic and can be mobilized and moved to a new drill site within four days. The unit, illustrated in Figure 5.1-16, is capable of completing two 5,000 m (16,000 ft) wells without resupply during the winter period. The existing SSDC was fabricated from a 10-year-old 250,000 DWT tanker. Part of the bow and stern were cut away and the sides were strengthened against ice forces by providing a 1 m (3 ft) thick concrete wall behind the side plates. Ballasting is by sea water. At water level the caisson is 162 m (531 ft) long and 53 m (174 ft) wide. The deck is cantilevered forward and aft to provide additional deck space.

The unit has already been deployed and is drilling wells in the Arctic. It is designed to sit on top of a berm and has operated in

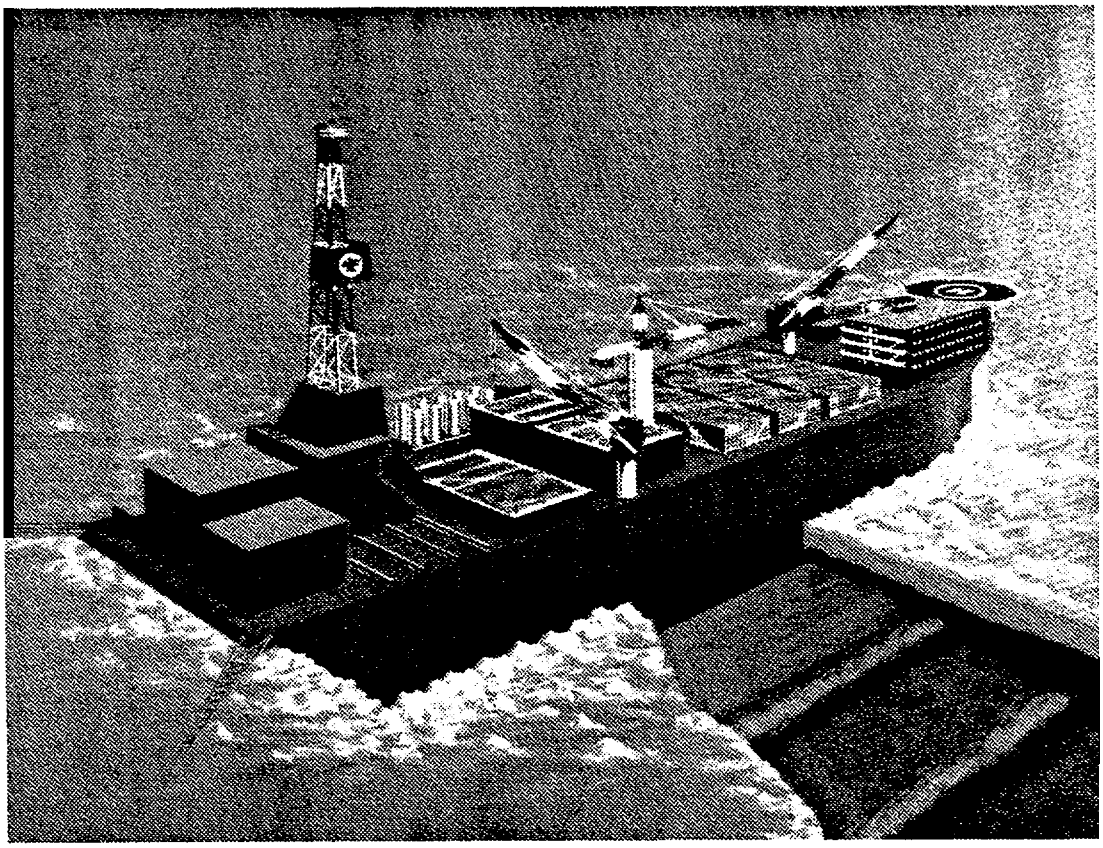

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Figure 5.1-16. Single Steel Drilling Caisson (SSDC).

31 m (103 ft) water depth with the top of the berm 9 m (30 ft) below the water surface. The berm was constructed with a 1:5 slope, designed to create a rubble field, and thus minimize the ice force on the hull. Additional protection against ice forces is provided by an ice barrier surrounding the structure. The barrier is constructed by spraying water to form an ice layer that grounds on the berm's slope (Cottrill, 1982).

## Mobile Arctic Island (MAI)

'The Mobile Arctic Island (MAI) drilling structure is a modified oil tanker which has the capacity to drill exploratory wells and handle production. MAI consists of a steel caisson founded on an underwater sand or gravel berm as illustrated in Figure 5.1-17. The caisson is constructed from an existing 250,000 DWT tanker by removing the bow and stern sections, cutting the mid-body in half transversely and assembling the two halves side by side. The steel structure is reinforced to withstand ice loading and ballasted with seawater. A concrete reinforced steel wedge placed along the side of the vessel acts as an ice-break. The concept is suitable for a range of water depths by varying the height of the underwater berm.

The 110 by 136 m (360 by 445 ft) structure will have a shallow draft enabling it to be put down in water as shallow as 4.5 m (15 ft) or as deep as 36 m (120 ft) with the additional construction of a gravel base. Individual platforms will be designed to meet specific

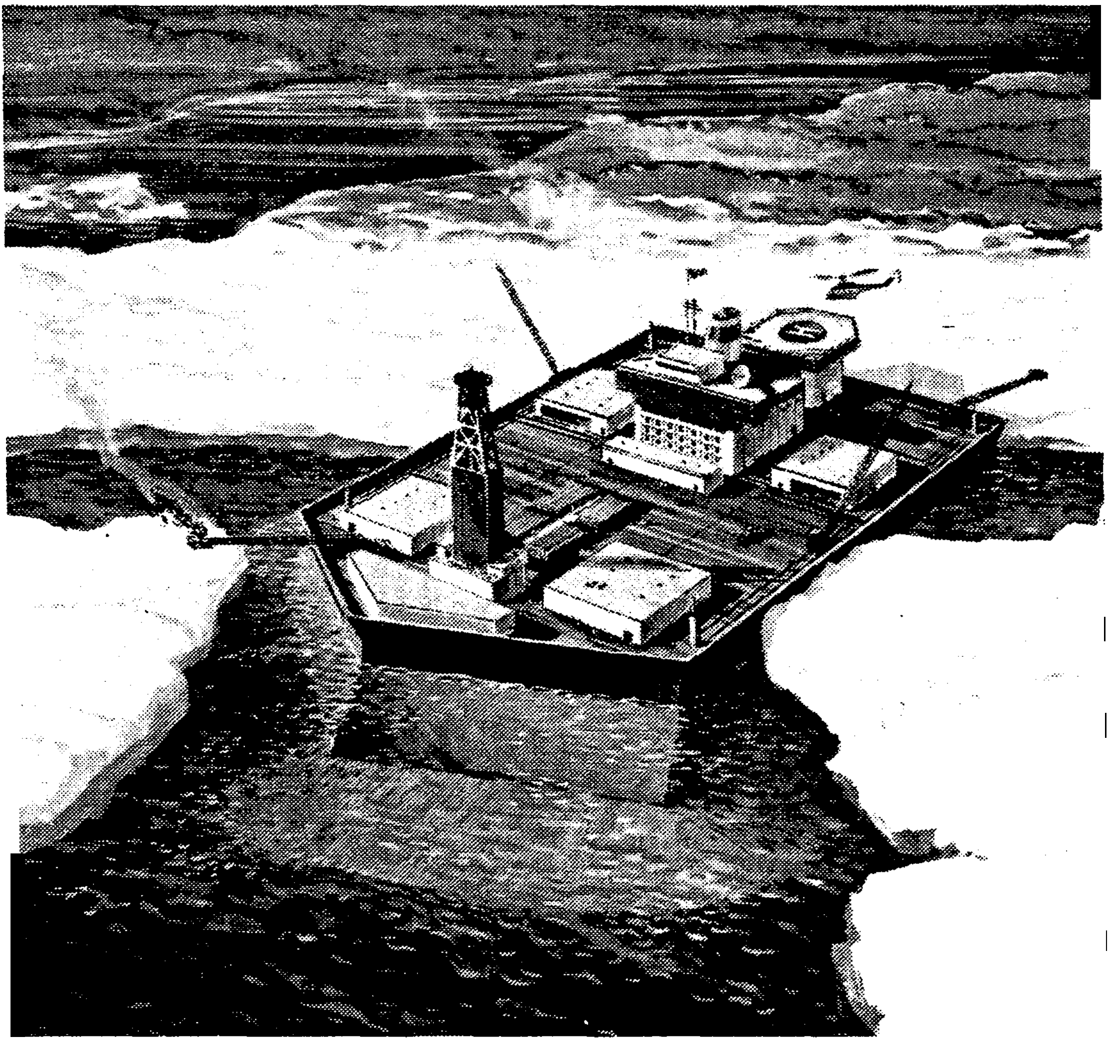

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Figure 5.1-17. Mobile Arctic Island (MAI).

exploration and production needs. Detail design of the exploration platform is complete and detail design of a production platform that can handle development of a 60-well field producing 300,000 BPD is also complete. The concept is applicable in the land fast and active shear ice zones. (ENR, October 25, 1984; Bow Arctic Resources Brochure, 1984; Berlie et al., 1984).

### Sonat Hybrid Arctic Drilling Structure (SHADS)

The Sonat Hybrid Arctic Drilling Structure (SHADS) illustrated in Figure 5.1-18, can be used for both exploration and production. It is constructed of an all steel base, mated to a steel and concrete midsection and topped by an all steel deck. The deck is surrounded by a wave and ice deflector. SHADS comes equipped with enough supplies to drill up to five wells without resupply, and is, of course, not subject to erosion from environmental forces. It is suitable for placing on soils ranging from weak to firm, resisting ice loads from floes up to 20 m (65 ft) thick, and operating in water depths of 7.5 to 20 m (25 to 65 ft). Greater water depths can be accommodated if the structure is placed on a prepared berm. The unit is easily relocatable and requires a minimum amount of time to move. The preliminary design of the unit is complete and concept approval has been obtained from the American Bureau of Shipping (Sonat Brochure, 1984).

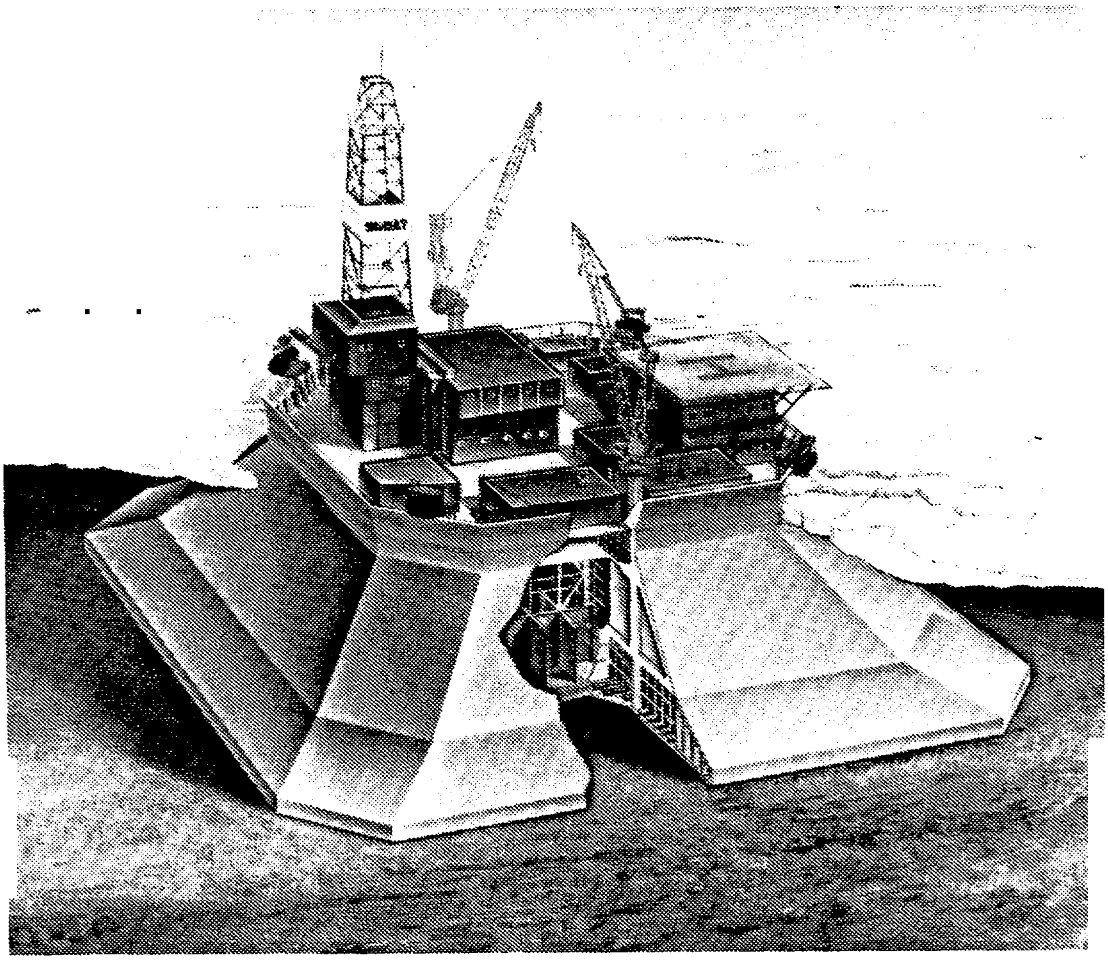

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Figure 5.1-18. Sonat Hybrid Arctic Drilling Structure (SHADS).

## Portable Arctic Drilling Structure (PADS)

The Portable Arctic Drilling Structure (PADS) is a double-walled cylindrical steel gravity structure that uses an internal surcharge of ballast water to develop foundation sliding resistance in cohesionless soils. The ballast water supports a platform (deck) on which drilling operations can be conducted. The rig is designed to resist the multiyear ice floes anticipated in the 6 to 15 m (20 to 50 ft) water depths of Harrison Bay. Its outer skin is capable of resisting ice contact pressures of 8 mPa (1,200 psi) acting over 2.5 $m^2$ (25 $ft^2$). As illustrated in Figure 5.1-19, a large flat circular barge serves as a two-level deck for the drilling equipment, crew quarters, and most of the drilling consumables (fuel and drilling water are stored in the substructure). The deck covers an area comparable to that of an artificial gravel island. Conventional Arctic land drilling rigs can be adapted for use on the deck. The deck floats on the ballast water during operation, and rests down inside the rig when PADS is under tow. The drill string passes through a centrally located, cylindrical moonpool, open at both ends. The top of the moonpool extends above the ballast water surface and through the deck. The structure will store consumables capable of sustaining operations for 270 days (three wells to 4,300 m [14,000 ft]). Preliminary design of PADS is complete.

Installation is accomplished by direct filling of the ballast holds with seawater. The rig can be set on bottom in less than ten hours. Complete ballasting will take about two days with the pumping

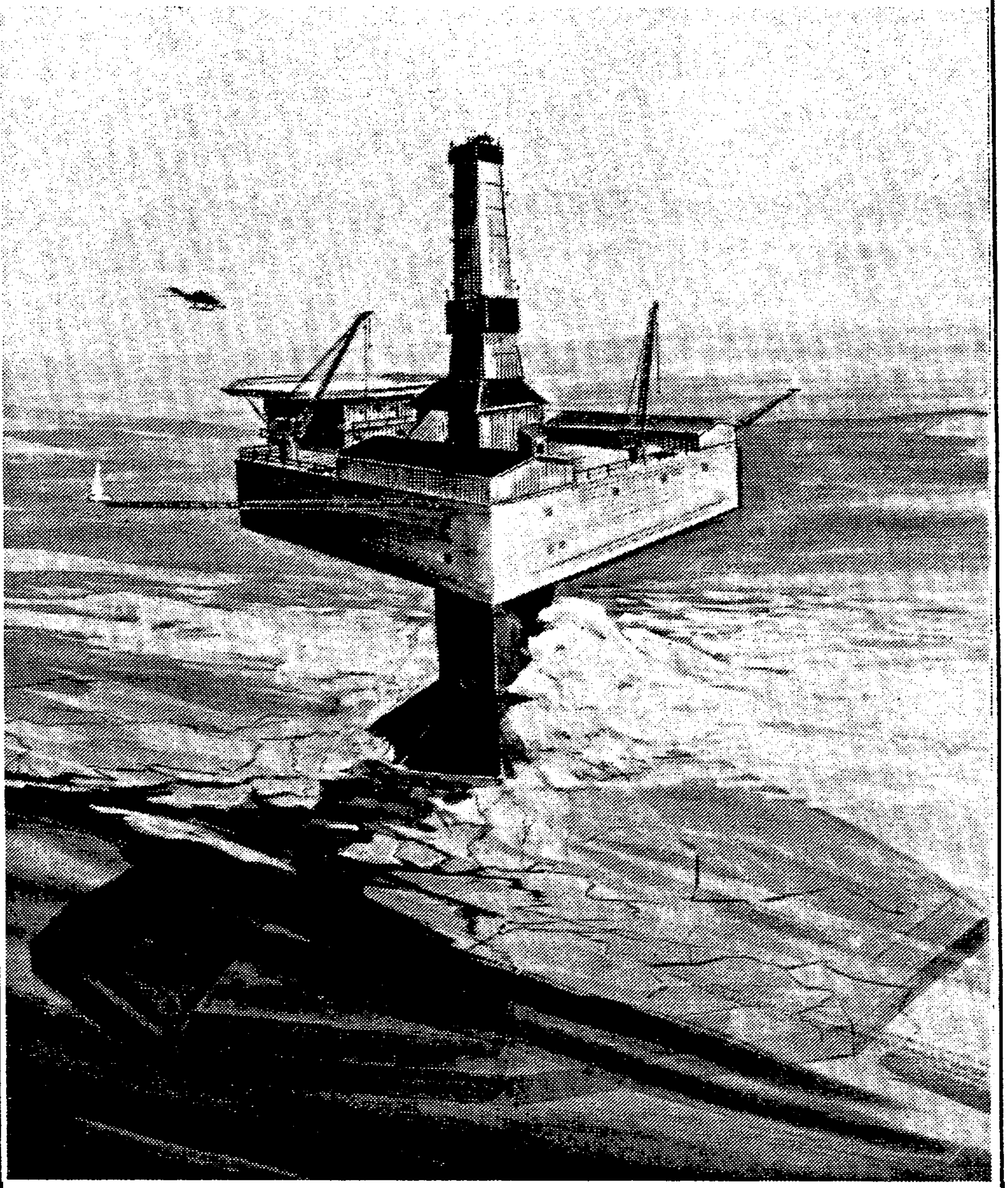

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Figure 5.1-20. Conical Monopod.

system presently planned. Rig relocation is accomplished by pumping out the ballast water, towing to the next location, and repeating the same ballasting procedure (CBI Brochure, 1984).

### Conical Monopod

The Conical Monopod is a 16-sided, steel/concrete gravity structure, as illustrated in Figure 5.1-20. The structure is designed to resist the multiyear ice features anticipated in the 9 to 23 m (30 to 75 ft) water depths of Harrison Bay. The outer surfaces of the base are sloped in order to decrease horizontal loading applied by impinging ice masses. Ice thrusting against the base also applies a vertical loading to the rig that adds to the unit's horizontal load capacity on cohesionless soils. 'The diameter across the flats at the bottom of the substructure is 125 m (410 ft), and the minimum diameter of the moonpool is 24 m (78 ft). The outer skin is a double-wall, all steel structure with diaphragms. All surfaces of the rig below elevation 30 m (100 ft) have been designed for ice contact pressure ranging from 10 mPa (1,500 psi) over 0.1 $m^2$ (1 $ft^2$) to 8 mPa (1,200 psi) over 2.5 $m^2$ (25 $ft^2$). The bottom is a single-skin construction with stiffeners and stringers. Loads are transferred through the structure with radial and circumferential bulkheads of composite steel/concrete construction. The overall height from the bottom of the unit to the upper deck is about 51 m (167 ft). The rectangular deck has two levels, each measuring 55 by 67 m (180 by 220 ft) with a resulting total deck area of 7,900 $m^2$

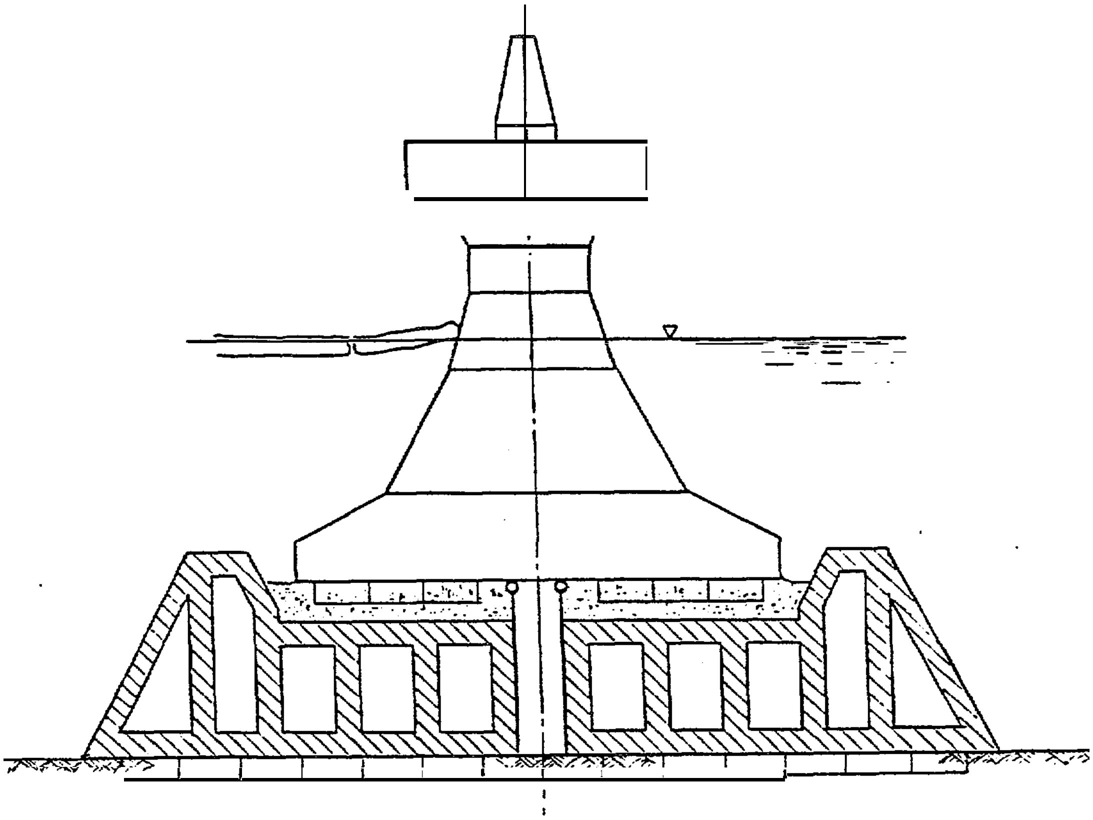

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Figure 5.1-21. Arctic Drilling Structure **with** Detachable Caisson Mat.

After the lower caisson is installed on the seabed, a layer of sand is placed on top and the upper section is lowered into position. The sand serves to transfer the ice loads between the two sections.

A significant advantage of the two-stage structure is that each unit can be towed around Point Barrow with a shallow draft. The Arctic Drilling Structure with Detachable Caisson Mat is being designed for operation in water depths up to 60 m (200 ft), but the concept is suitable for deeper water also (Mitsui Personal Communication, 1984).

### BWA Arctic Steel Pyramid

The BWA Arctic Steel Pyramid (WASP), illustrated in Figure 5.1-22, is a mobile exploration structure which is designed utilizing steel/concrete composite construction techniques, Internally, BWASP has a grid of steel circumferential and radial walls, but its sloping outer face is formed by a composite steel plate and infill concrete sandwich.

The unit is in the preliminary design stage. The initial design is aimed at Beaufort Sea water depths of 10 to 12 m (30 to 40 ft) in the severe ice of the shear zone. However, other versions of the same concept have been developed for water depths of up to 36 m (120 ft). (Offshore Engineer, November 1984).

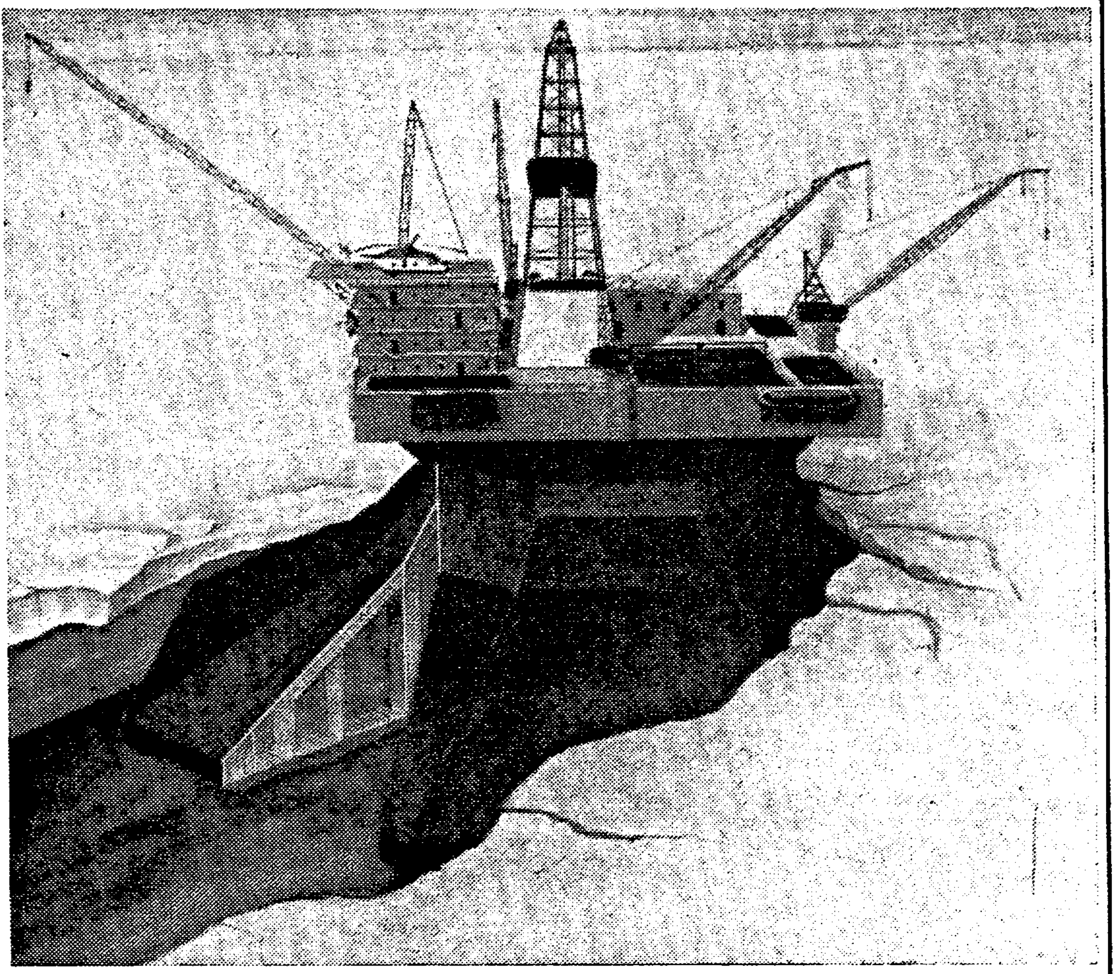

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Figure 5.1-22. BWA **Arctic** Steel Pyramid.

## Mobile Arctic Gravity Platform

The Mobile Arctic Gravity Platform, Illustrated in Figure 5.1-23, is an exploratory drilling system that is geared toward operation in 20 to 50 m (65 to 165 ft) of water. The unit provides a year-round, mobile platform capable of drilling three deviated wells without major resupply, or, alternately, for a single well case, is able to achieve two moves during the short Arctic open water season. The base of the unit is a double angle 45°/700 cone, the 70° cone providing a transition into a cylindrical stem. At lesser water depths, ice will ride up on one of the lower cones and fail in bending, while at greater depths the ice will crush against. the vertical cylinder. The base is comprised of a “spoke” configuration, the spokes being water ballast tanks which connect to circumferential ballast tanks. Spaces between the spokes are left open and then filled with sand ballast in place to improve sliding resistance. Sand ballast can be removed by a small dredge or airlift prior to refloating.

At the present time, a conceptual design for the Mobile Arctic Gravity Platform has been developed. Although a preliminary investigation showed that a movable gravity concept is viable for the Beaufort Sea environment, more work is required to define the ice-structure interaction and the capability of the anchoring system during setting and raising.

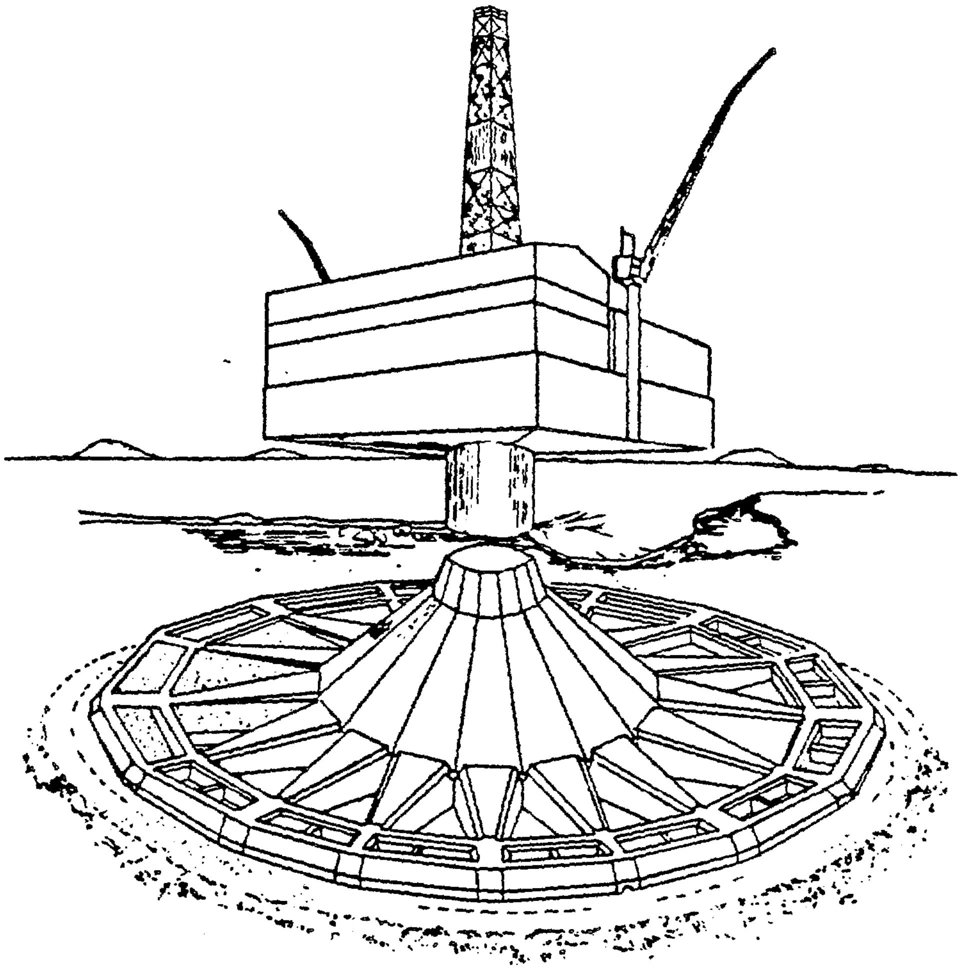

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*Figure* 5.?-23. Mobile Arctic Gravity Platform.

The Mobile Arctic Gravity Platform conceptual design provides for operation in 20 to 50 m (65 to 165 ft) of water, but the construction of a sand berm could increase the depth capability to 60 m (200 ft) or more. In determining the foundation dimensions, the following three ice loading scenarios were considered:

- 16 m (52 ft) thick ice sheet with unlimited driving force,
- first and multiyear ice ridges driven by a thick first year pack, and
- rubble formations grounded on the structure and interacting with the first year pack.

Due to the loss of stability with reduction in waterplane area as the structure is submerged during the installation process, a multipoint anchor system is required to pull the structure down in water depths beyond 30 m (100 ft). This requires careful coordination between the ballasting and winching operations so that positive buoyancy is maintained at all times (Wasilewski and Bruce, 1981).

### Bottom Mounted Ice-cutting Platform

The Bottom Mounted Ice-cutting Platform, which is an extension of the Ice-cutting Semi-submersible Drilling Vessel (ICSDV), is illustrated in Figure 5.1-24. The central platform features a 100 m (330 ft) square or circular hull , a central column 10 m (30 ft) in

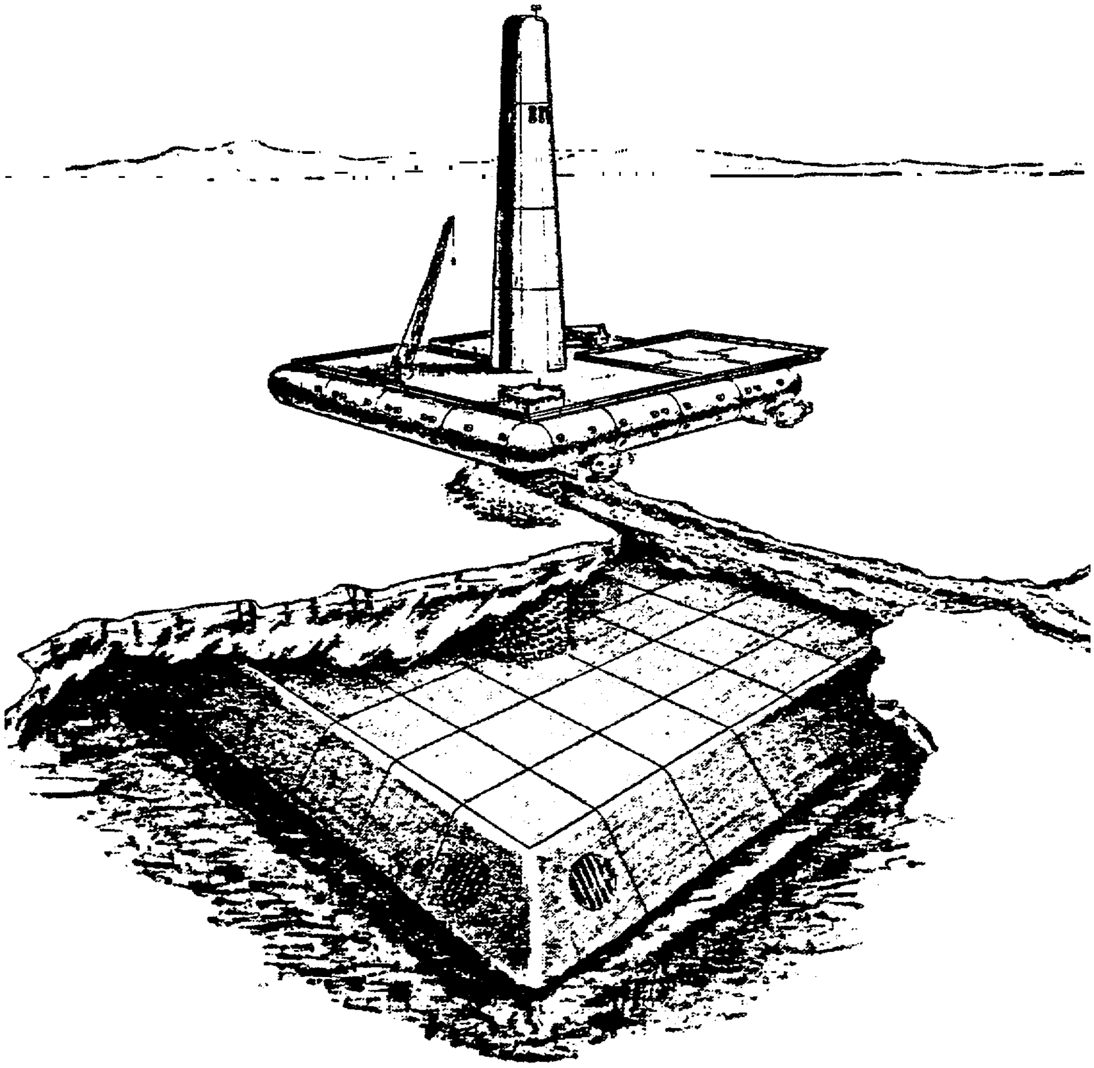

Figure 5.1-24. Bottom Mounted Ice-cutting Platform.

diameter, and 50 m (160 ft) square superstructure. Rotating ice-cutting blades are positioned on the central column.

The platform is designed with a column height sufficient to allow the highest ice ridge that could move into the given area to pass beneath the upper hull without contacting it. Location is maintained through bottom friction as all ballast tanks are flooded to provide sufficient weight to counter pressure ridge keels that are deep enough to hit the lower hull. The sides of the lower hull are shaped to precipitate breakage of the ice keel and increase the downward force (Sea Log Brochure, 1984).

## Zee Star Arctic Mobile Drilling"Rig

The Zee Star Arctic. Mobile Drilling Rig is illustrated in Figure 5.1-25. The structure's design is based on the space frame principle, permitting an optimum distribution of the forces and therefore a minimization of concrete quantities as well as reinforcement and prestressing. The structure is up to 20 percent lighter than conventional concrete construction with diaphragm walls. The space frame principle for the design is combined with an industrial precasting system and methods of assembly.

The construction method is based on a maximum of prefabrication of the various parts constituting the structure, using normal weight concrete. The repeated use of individual elements, the 450 slab

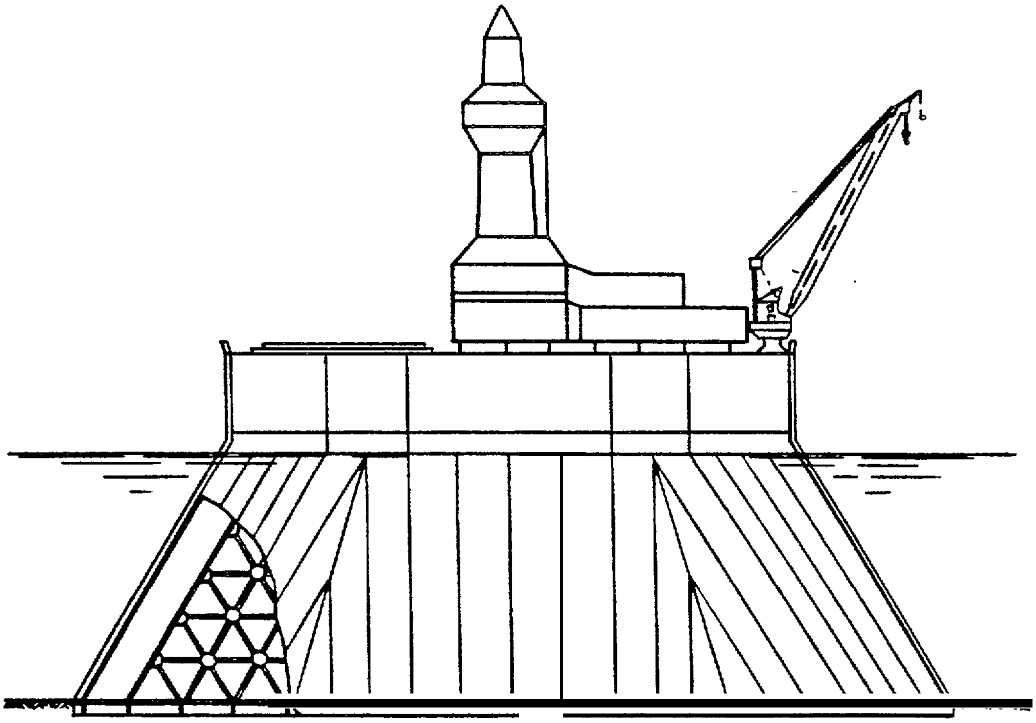

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Figure 5.1-25. Zee Star Arctic Mobile Drilling Rig.

elements and 1200 crystal elements, allows for industrial precasting, thus producing high quality concrete. Those parts of the structure that are difficult to cast are prefabricated, leaving only simple sections to be cast in-situ.

The Zee Star Arctic Mobile Drilling Rig would be fully outfitted at the construction site with necessary equipment, storage facilities for two wells, living quarters, and a drilling rig. A second deck, located 15 m (50 ft) below the steel drilling deck, contains the quarters, storage and other facilities and is completely protected from the weather. The unit can stay on location for 270 days without resupply.

The unit, which is in the conceptual design stage, can be installed in 13 to 40 m (43 to 130 ft) of water, and is designed to resist the most severe ice forces in addition to the very poor soil conditions of the Beaufort Sea. It requires no site preparation or subsea berm other than a reasonably level seabed. Skirts located in its 130 m (425 ft) square base can be totally or partially eliminated (Offshore, November 1984).

### Arctic Composite Platform (ARCOP)

The Arctic Composite Platform (ARCOP) can be used for exploration, development drilling, and/or production. The structure can initially be used as a drilling structure and ultimately converted to a production structure by modular retrofitting on site or at a southern location. The structure is mobile, and enough equipment and supplies can be accommodated to drill and operate, unsupported, through a complete winter season. It can be used year round at almost all Arctic locations.

ARCOP was designed as an alternative to the gravel island. The structure consists of an exterior conical concrete shell stiffened by radial walls, as illustrated in Figure 5.1-26. Steel is used for interior framing and deck members of the conical structure to reduce weight and draft. The concrete resists the ice forces. To further reduce weight, concrete which is not exposed directly to ice is lightweight. The minimum" draft is less than 9 m (30 ft), readily permitting passage around Point Barrow and making them suitable for applications in very shallow water depth. for applications in very shallow water depth. Where operation is to be on relatively weak seabed soils, spud piles can be used to resist lateral load. Shallow skirts are also provided below the base to aid in mobilizing foundation soils to resist sliding.

ARCOP is in the conceptual design stage. It can be used in water depths of 10 to 20 m (33 to 65 ft). However, the use of a sand berm allows the upper bound to be increased beyond 20 m (65 ft ). It is designed to resist multiyear floes and large pressure ridges in the landfast ice zone (Offshore, November 1984; Fluor-Davis Brochure, 1984).

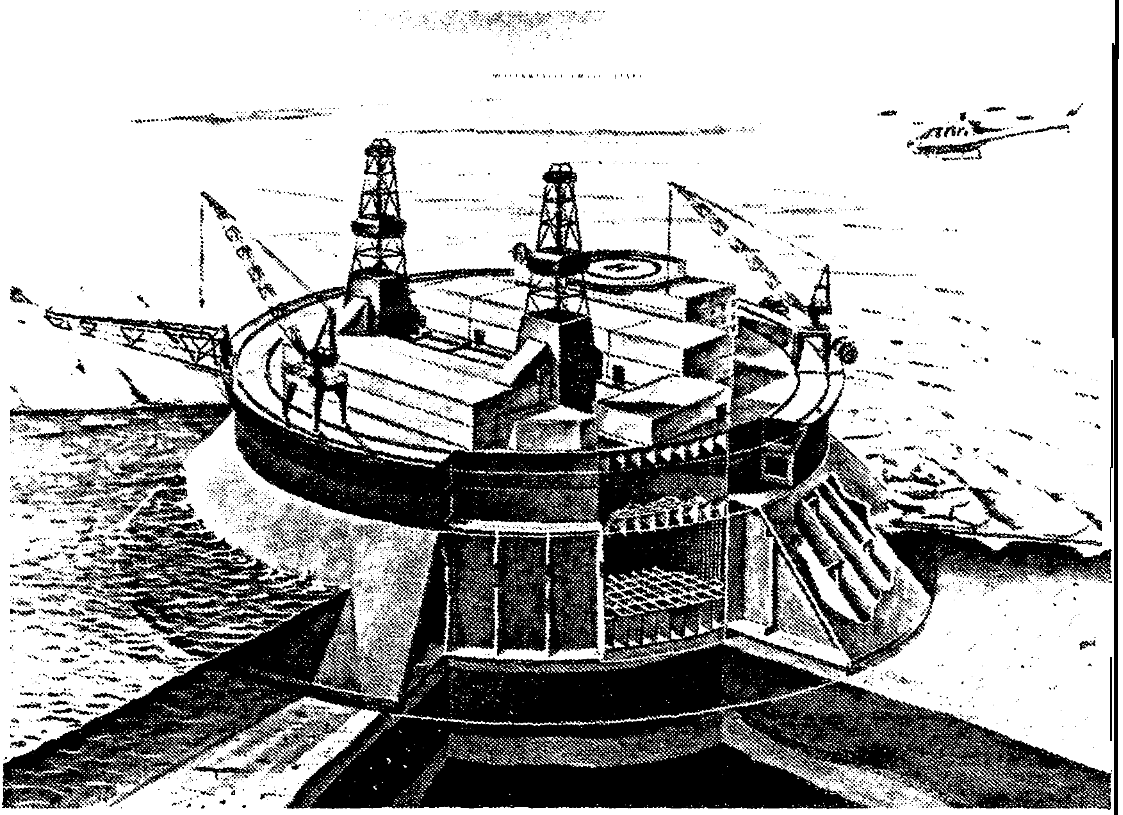

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Figure 5.1-26. Arctic Composite Platform (ARCOP).

### Summary

A summary of the various Bottom Founded exploration platform concepts is presented in Table 5.1-2.

## 5.1.3 Floating Concepts

### Conical Drilling Unit (Kulluk)

The Conical Drilling Unit, named **Kulluk,** illustrated in Figure 5.1-27, is a floating exploration platform which is towed from site to site. It is capable of drilling wells to a maximum depth of 6,100 m (20,000 ft), and has a storage capacity sufficient for 60 days of uninterrupted operation. The double hull of **Kulluk** is in the form of an inverted cone, which flares out at the bottom, causing the ice to break downward away from the vessel, protecting its drilling riser and mooring lines. The unit is moored on location by radially deployed anchor lines. The rig anchor release system may be acoustically activated in case of emergency. Probability of survival of the vessel under the most extreme conditions is high, even assuming mooring system failure. The hull is segmented by eight radial and two circumferential watertight bulkheads. All areas exposed to ice are double hulled.

The rig has been in use in the Canadian Beaufort Sea since 1983.

## TABLE 5.1-2

## SUMMARY OF BOTTOM FOUNDED EXPLORATION PLATFORMS

| CONCEPT NAME | FIG. NO. | MAXIMUM WATER DEPTH (m) | PRESENT STATUS |
|---|---|---|---|
| Arctic Cone Exploration Structure | 5.1-7 | 33 | Proposed |
| Mobile Arctic Caisson | 5.1-8 | 40 | Operational |
| Arctic Mobile Drilling Structure | 5.1-9 | 18 | Proposed |
| Mobile Gravity Platform | 5.1-10 | 41 | Proposed |
| Monopod Jack-up Drilling Rig | 5.1-11 | 27 | Detail Design |
| Mobile Arctic Drilling Structure | 5.1-12 | 12 | Proposed |
| Sohio Arctic Mobile Structure | 5.1-13 | 18 | Detail Design |
| Concrete Island Drilling System | 5.1-14 | 17 | Operational |
| BWA Caisson System | 5.1-15 | 18 | Proposed |
| Single Steel Drilling Caisson | 5.1-16 | 31 | operational |
| Mobile Arctic Island | 5.1-17 | 36 | Detail Design |
| Sonat Hybrid Arctic Drilling Structure | 5.1-18 | 20 | Proposed |
| Portable Arctic Drilling Structure | 5.1-19 | 23 | Proposed |
| Conical Monopod | 5.1-20 | 23 | Proposed |
| Arctic Drilling Structure with Detachable Caisson Mat | 5.1-21 | 60 | Proposed |
| BWA Arctic Steel Pyramid | 5.1-22 | 36 | Proposed |
| Mobile Arctic Gravity Platform | 5.1-23 | 50 | Proposed |
| Bottom Mounted Ice-cutting Platform | 5.1-24 | 55 | Detail Design |
| Zee Star Arctic Mobile Drilling Rig | 5.1-25 | 40 | Proposed |
| Arctic Composite Platform | 5.1-26 | 20 | Proposed |

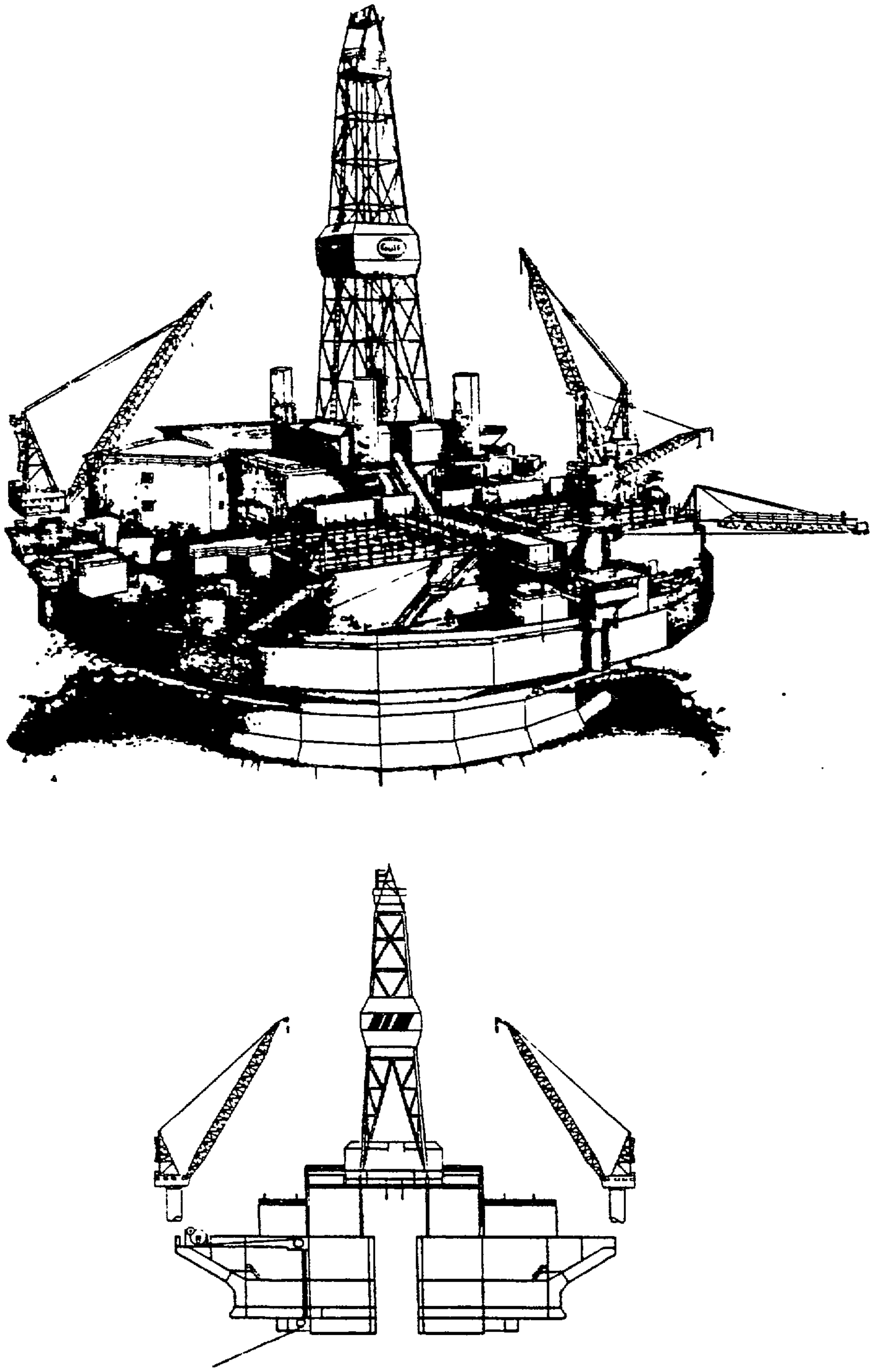

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Figure 5.1-27. Conical Drilling Unit (Kulluk).

Its design water depth limitation is 24 to 55 m (79 to 180 ft). Kulluk is designed to operate when exposed to a 1.2 m (4 ft) ice sheet having a flexural strength of 755 kPa (110 psi), a 55 km per hr (33 mph) sustained wind and a 0.3 m per sec. (1 fps) current velocity. In order to withstand the more severe large first-year ridges and multiyear ice, the vessel requires an ice management system. During open water conditions, the rig is designed to operate when exposed to a significant wave height of 2.8 m (9 ft), a 45 km per hr (27 mph) wind and a 5 m per sec (16 fps) current. Under survival conditions, the mooring system is designed to release from the anchors before the load reaches the system's breaking strength (Gaida et al., 1983; Ocean Industry, June 1982).

### Egg-shaped Ice-resistant Barge

The Egg-shaped Ice-resistant Barge, as illustrated in Figure 5.1-28, is designed for severe ice or deep open water. It is narrower than a round barge for the same deck area and therefore has less exposure to ice forces. The bow is circular and wider than the stern, and there is a turret which is moored to the seafloor. The drillship weathervanes about the turret in moving ice. The conceptual design has been completed.

As a safety measure, the barge has an ice protector around the underside of the moonpool to prevent broken ice from entering. The rig is designed for a 1.7 m (5.5 ft) level ice thickness during

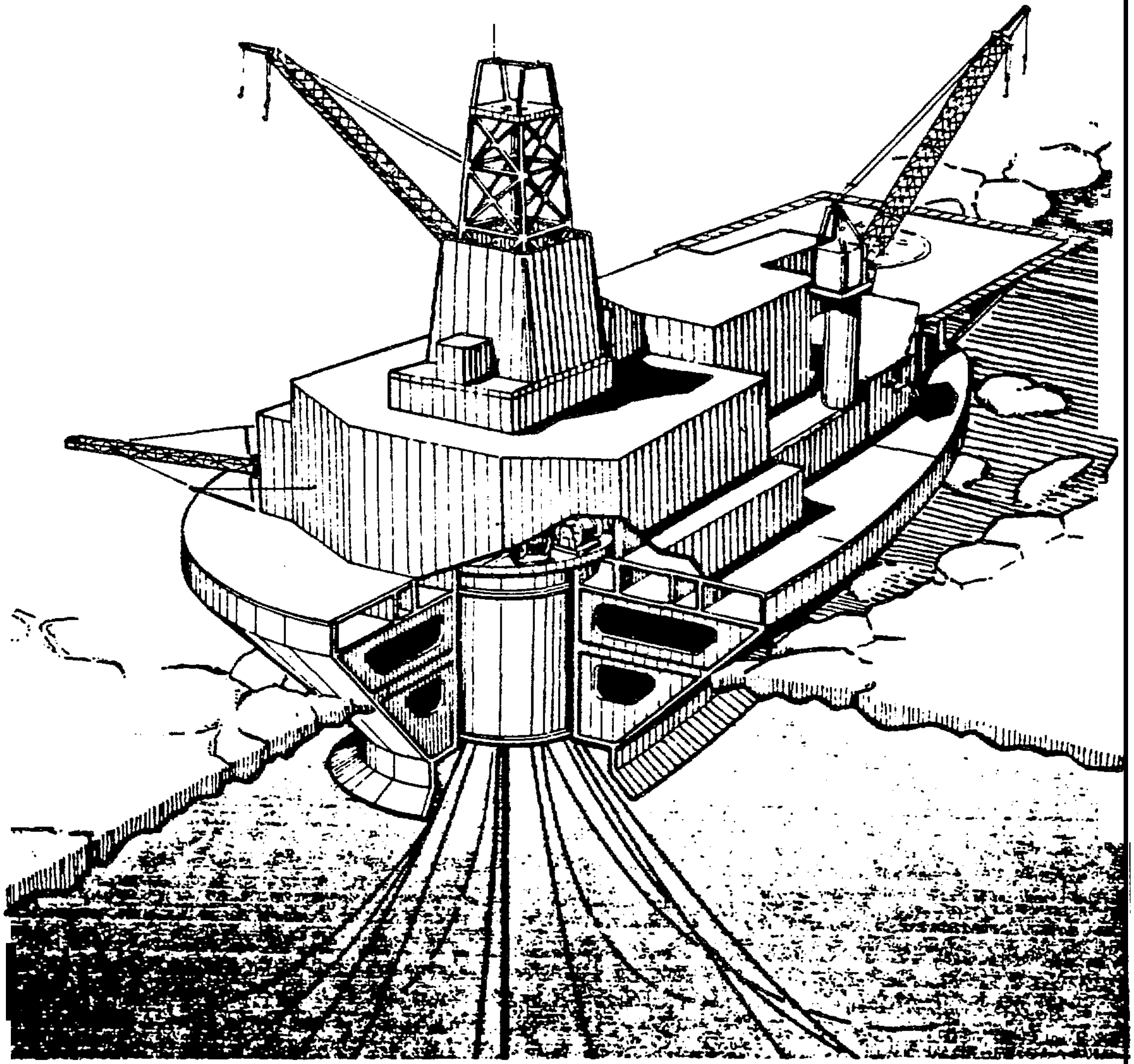

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**Figure** 5.1-28. Egg-shaped Ice-resistant Barge.

drilling and a rafted ice and effective first-year ridge thickness of 2.4 m (8 ft). It would be capable of operating in water depths of 21 to 61 m (70 to 200 ft) and withstanding a significant wave height of 9 m (30 ft) (Offshore Engineer, September 1982; Mitsui Brochure, 1984).

### Swivel Drillship

The Swivel Drillship, illustrated in Figure 5.1-29, is an "ice drilling barge" which is suitable for drilling over a long drilling season in the Beaufort Sea. It differs from conventional drill ships in its Class 10 hull reinforcement and its turret mooring swivel under-the foredeck. The drilling rig sits within the turret and 16 mooring lines anchor the turret, enabling the bow of the ship to weathervane into the moving ice. Steel construction is proposed. It is in the conceptual design stage and estimated displacement is about 30,000 tonnes (Ocean Industry, April 1980).

### Ice-cutting Semi-submersible Drilling Vessel (ICSDV)

The Ice-cutting Semi-submersible Drilling Vessel (ICSDV) has a cylindrical hull which supports a cylindrical shaft which in turn supports a rectangular two-story deck structure. Drilling is accomplished through a central moonpool. The ICSDV is illustrated in Figure 5.1-30. The 11.5 m (38 ft) diameter column is fitted with a revolving cutter sleeve with 2 m (6 ft) teeth. The cutter sleeve

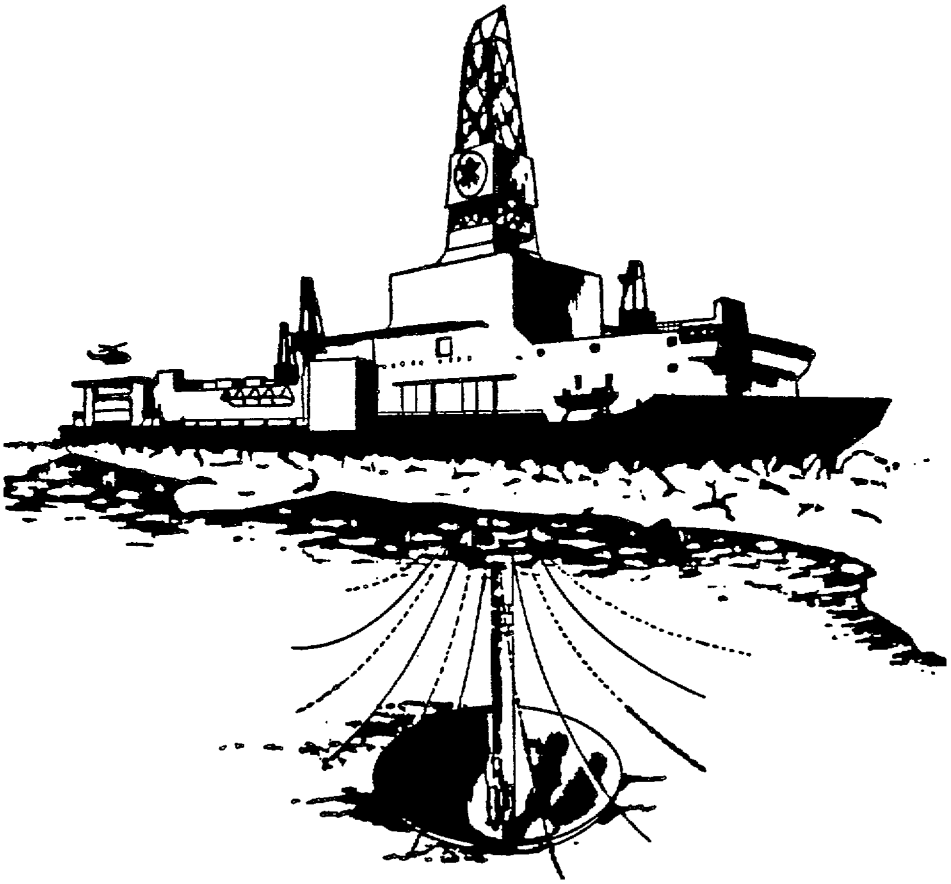

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Figure 5.1-29. Swivel Drillship.

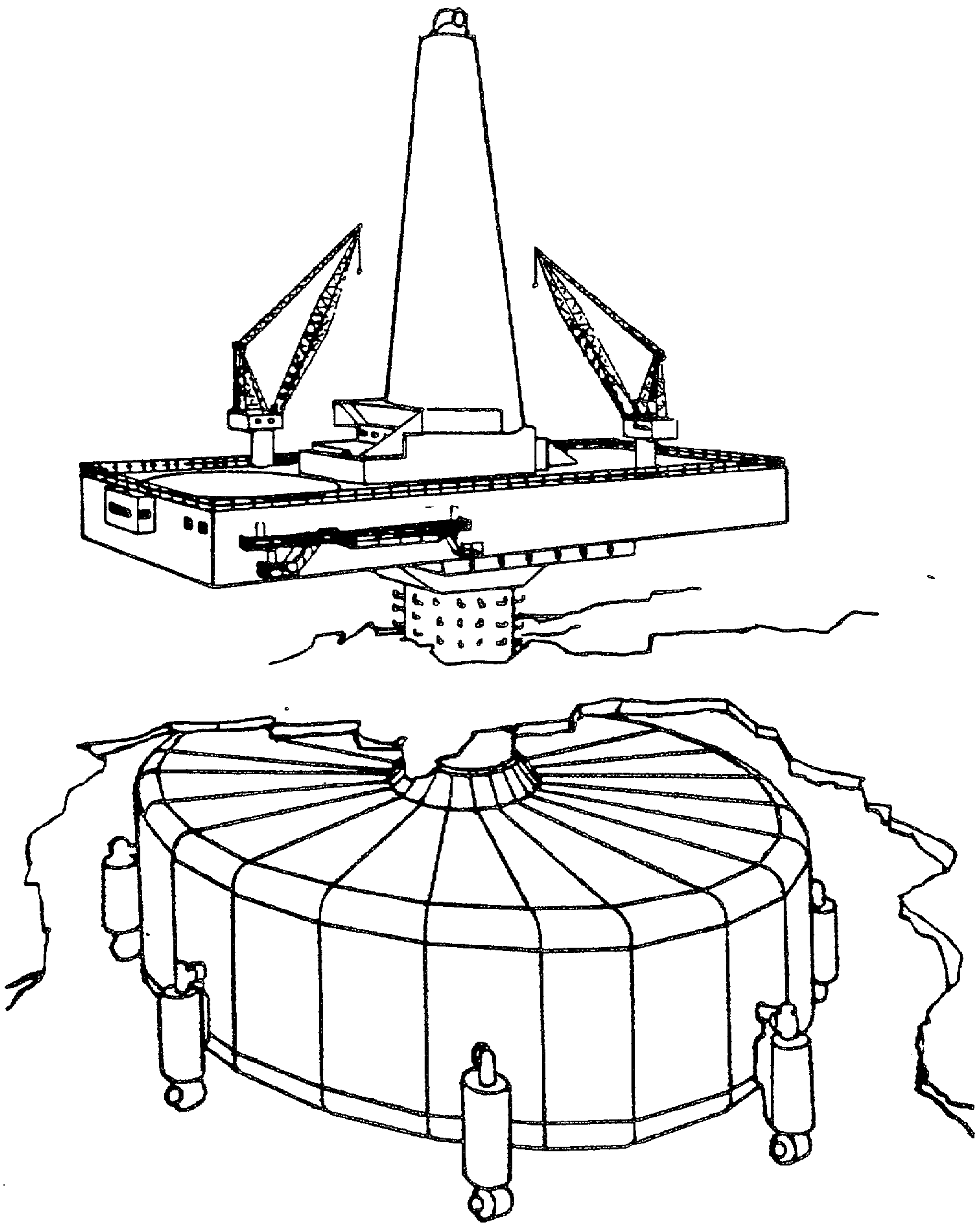

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**Figure** 5.1-30. Ice-cutting Semi-submersible Drilling **Vessel (ICSDV).**

actively cuts through the moving sea ice. Thrusters are used to keep station, move forward, and balance the torque from the rotating sleeve.

The self-propelled structure was designed to cut 12 m (39 ft) multiyear ice at 1.2 m per min (4 ft per rein), with 90,000 hp and a displacement of 110,000 tonnes. It is suitable for water depths of 100 to 500 m (300 to 1,500 ft). The ICSDV has been developed through the preliminary design stage (Offshore Engineer Supplement, August 1981).

### Arctic Drill Hull

The Arctic Drill Hull, illustrated in Figure 5.1-31, is intended to extend the Arctic drilling season by six months. It is 46 m (150 ft) in diameter, has a 12.5 m (41 ft) draft, and displaces 10,000 tonnes. It can accommodate a crew of 40. The Arctic Drill Hull is a conical-shaped floating platform moored to the seabed by a pretensioned anchor system. The hull has the capability of breaking ice by riding up and producing a downward force on the advancing ice. The holding capability of two of the eight anchor legs is considered to be available for resisting the ice force from any direction. The system has the ability to let go should ice forces become too great to maintain position. The wellhead is protected against damage from drifting ice by being installed in a subterranean chamber.

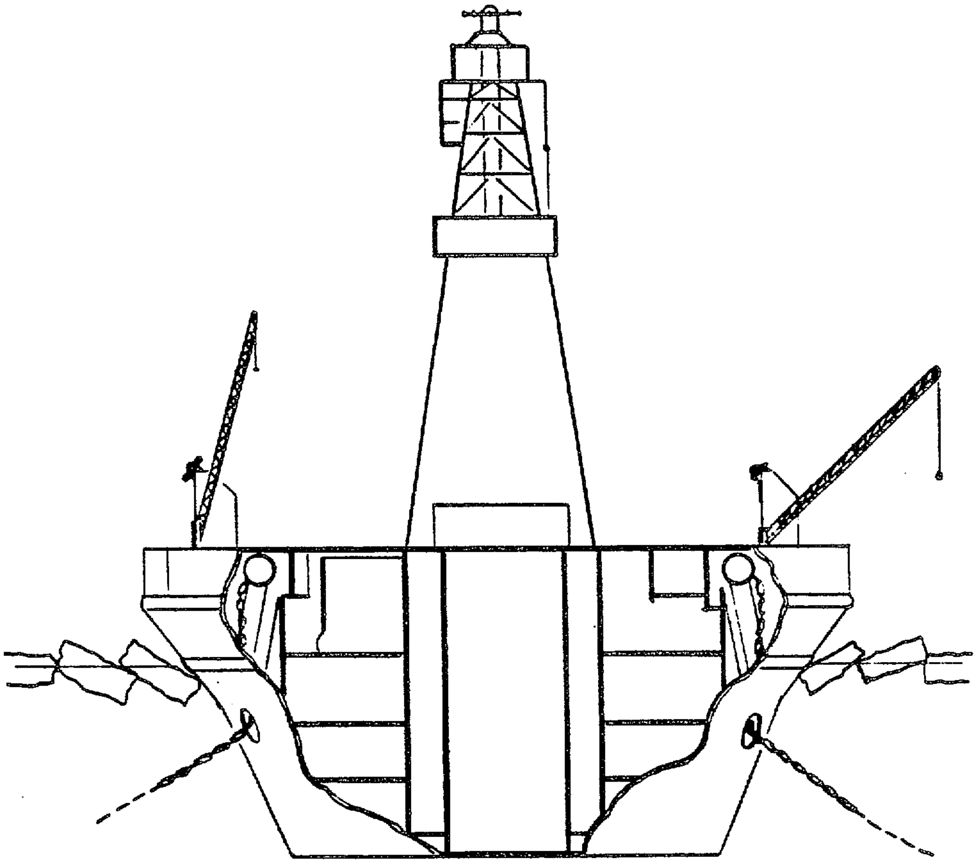

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Figure 5.1-31. Arctic Drill Hull.

The system is in the preliminary design stage. It is designed to operate in 18 to 180 m (60 to 600 ft) of water, however, it would be limited to the land fast ice zone in the Beaufort Sea as only up to 1.5 m (5 ft) fast ice accumulations can be resisted during operation (Ocean Industry, June 1971). ,

## Ice-Class Semi-submersible (Ice Maiden)

The Ice Maiden is the first semisubmersible purposely designed for Arctic waters. With an operational displacement of 41,000 tonnes, it is probably the largest vessel of its kind in the world. The Ice Maiden is illustrated in Figure 5.1-32.

Heat and mechanical systems reduce the effects of the ice loads. Blisters on the columns minimize ice adhesion and mechanical equipment may be used to break up the ice. Also, the rig's pontoons are designed for ice-breaking. The vessel will have a dynamic positioning system which, together with the mooring system, will enable the unit to meet the necessary stability requirements under the ice loading. The Ice Maiden is in the preliminary design stage. It is being designed to operate in the deepest and most severe Arctic regions (Ocean Industry, August 1981).

## Ice-resistant Semi-submersible Drilling Unit

The Ice-resistant Semi-submersible Drilling Unit, illustrated in

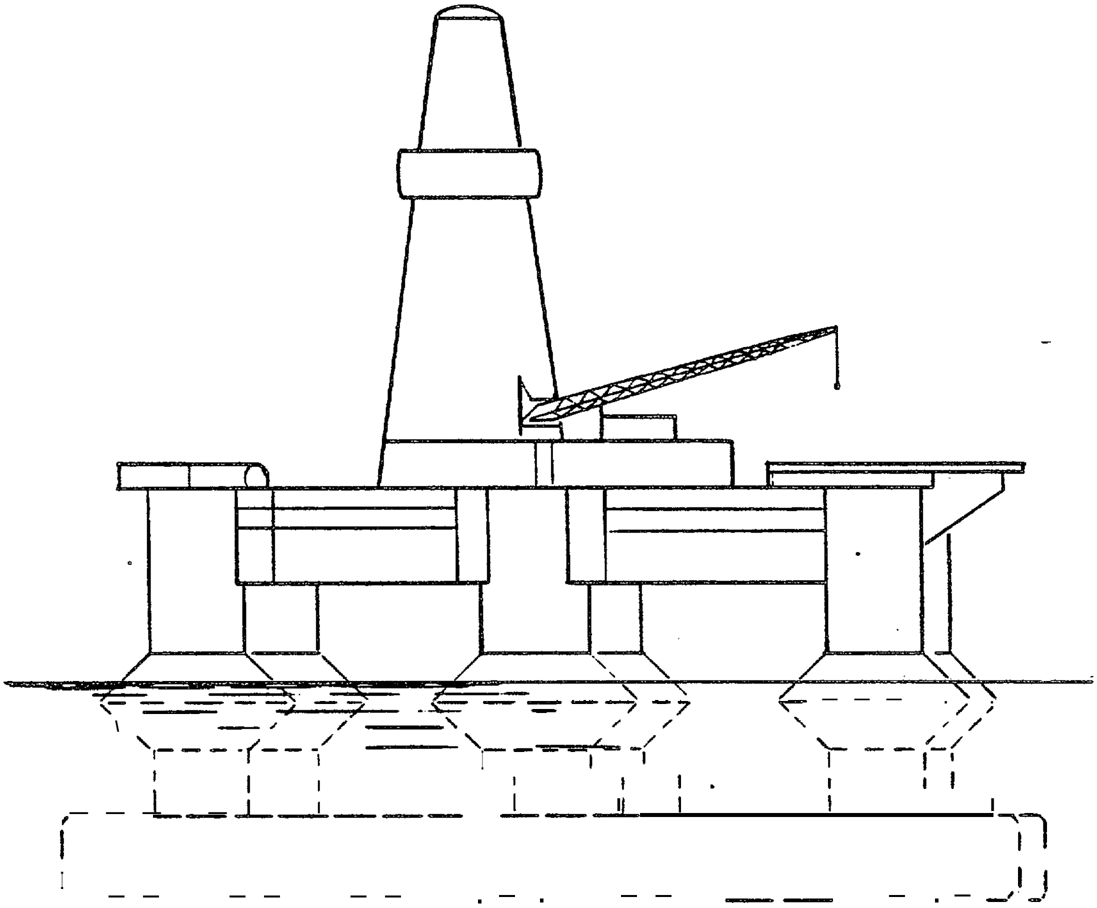

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**Figure 5.1-32.** Ice-Class Semi-submersible (Ice Maiden).

Figure 5.1-33, is designed to operate year-round in the ice-covered waters of the Beaufort Sea. For water depths of 20 m (65 ft) and less it is designed to operate as a bottom supported unit. This feature increases the unit's range of water depth operations. The unit resembles a typical semi-submersible but it has no struts or bracing members which pass through the waterplane. This minimizes interaction with the ice. Structurally, the unit consists of a deck resting on four columns, a riser protector and two lower hulls, each of the lower hulls supporting two of the columns. Ice forces on the columns and riser protector are reduced by the use of a compound inverted cone with a low angle at the water surface. In ice, the unit is ballasted so that these cones are at the ice level.

The Ice-Resistant Semi-Submersible Drilling Unit is in the conceptual design stage. Model tests were carried out for application of the unit in 160 m (530 ft) water depths in the floating mode. The semi-submersible will have to pull out and drift with ridges having a keel of more than 26 m (84 ft) (Corona and Nobuyoshi , 1983).

### Arctic Drilling Barge

The Arctic Drilling Barge, illustrated in Figure 5.1-34, could be an economically attractive alternative to gravel islands in the land fast ice zone. Because of its mobility, it could be used to drill more than one well per year at different locations. It is

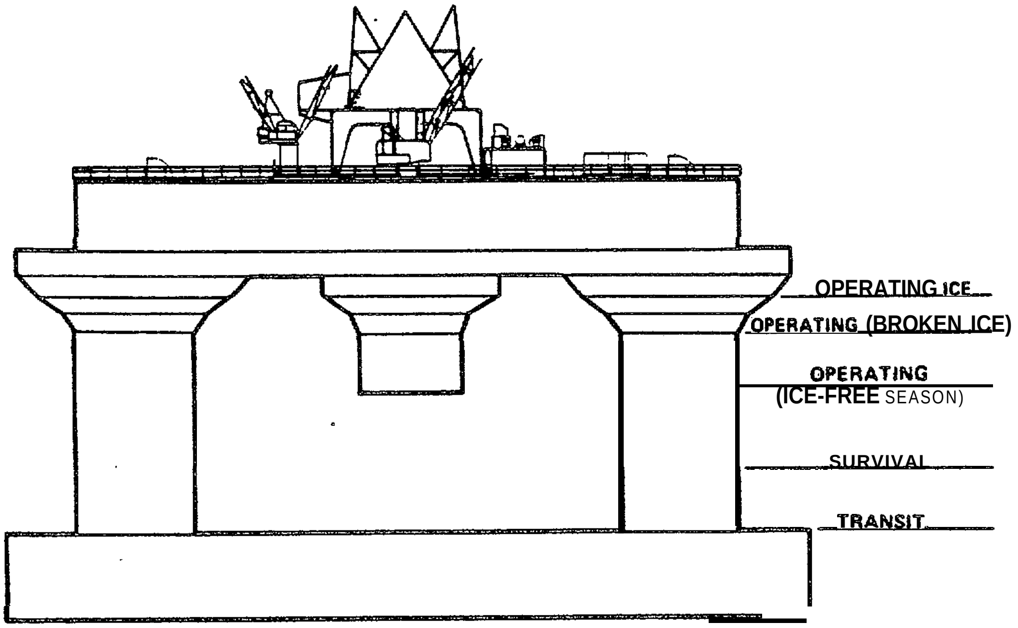

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**Figure 5.1-33.** Ice-resistant Semi-submersible **Drilling Unit.**

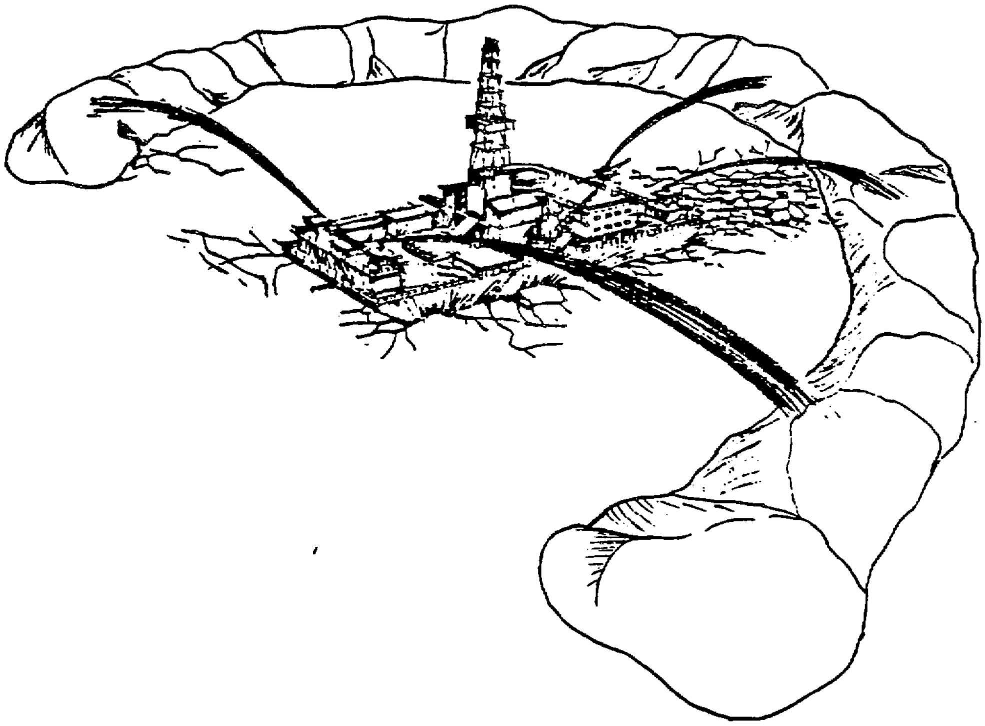

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Figure 5.1-34. Arctic Drilling Barge.

presently in the conceptual design stage. The unit is considered usable in 6 to 18 m (20 to 60 ft) of water in the Beaufort Sea.

The concept involves the mounting of a drilling system on a barge which can break the ice as it is moved by tugboats. The barge would be equipped with a unique feature giving it the capability to provide protection against the surrounding ice. Large water cannons, similar to those used on fireboats, would be mounted on the barge to spray water at a rate of more than 40,000 liters (10,000 gal) per minute around the seaward sides of the drilling site. This would create a grounded barrier of ice encircling the barge on three sides and protecting it from sea--ice movements. Access to the barge would be by way of its shoreward end over ice roads (The Lamp, 1982).

### Round Drillship

The Round Drillship, illustrated in Figure 5.1-35, has a 65 m (213 ft) diameter hull conforming to Arctic Class 6 and contains 10,000 metric tonnes of steel. It is shallow and saucer-shaped to minimize resistance to ice approaching from any direction. Mooring lines are attached to a small central cone which extends below the ice. With icebreaker support, the Round Drillship is intended for year-round drilling in the transition ice zone. It is in the preliminary design stage (Offshore Engineer Supplement, August 1981).

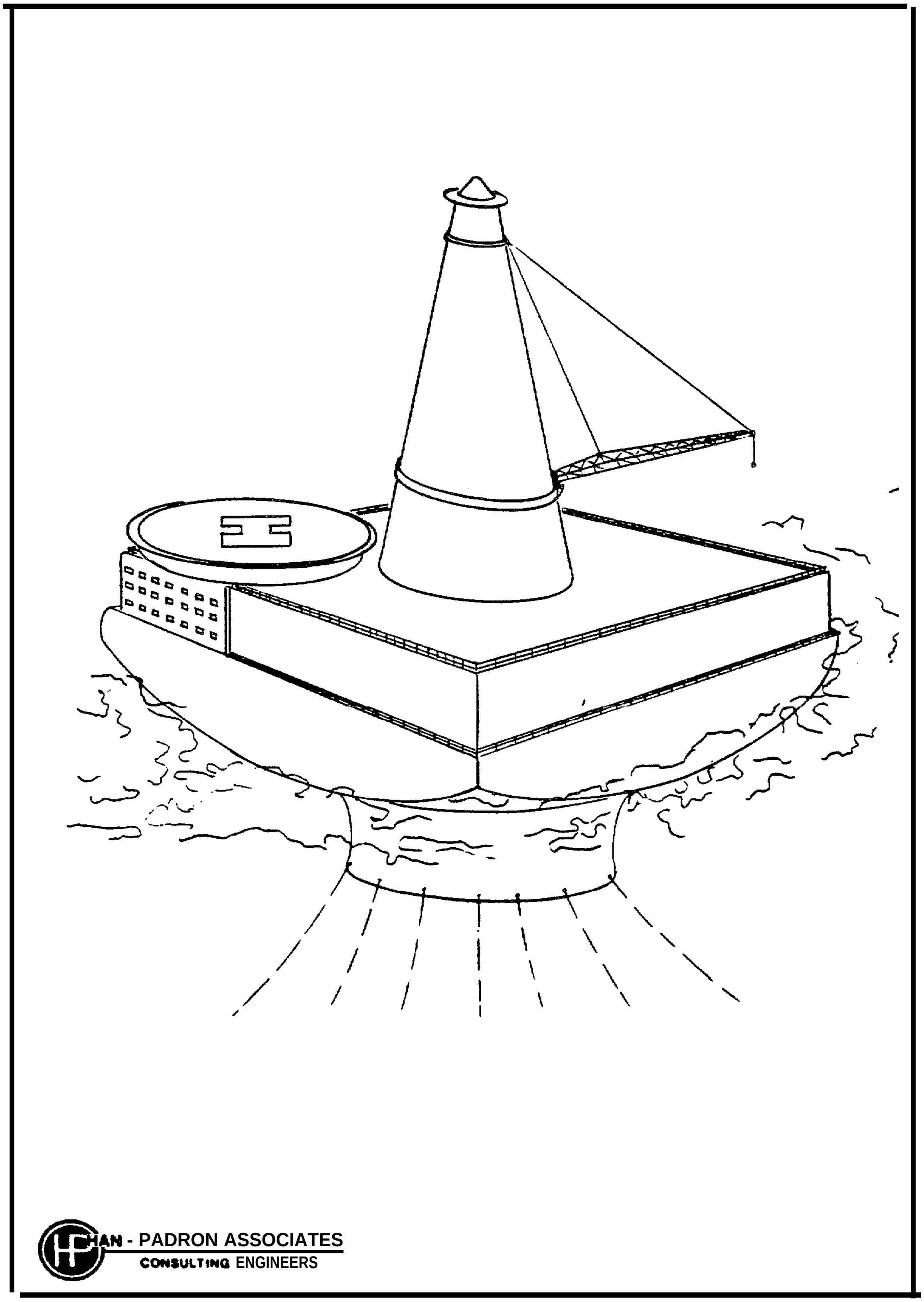

Figure 5.1-35. Round **Drill ship.**

## Conventional Drilling Vessels

Conventional drilling vessels have been used in the Canadian Beaufort Sea for exploration drilling during the open water season. A typical turret-moored ship-shaped drilling vessel is illustrated in Figure 5.1-36 and a typical semi-submersible drilling vessel is illustrated in Figure 5.1-37. Due to the motion of these vessels in waves and the consequent flexing of the drilling riser, the vessels are limited to operating in water depths greater than approximately 20 m (65 ft).

## Summary

A summary of the various Floating exploration platform concepts is presented in Table 5.1-3.

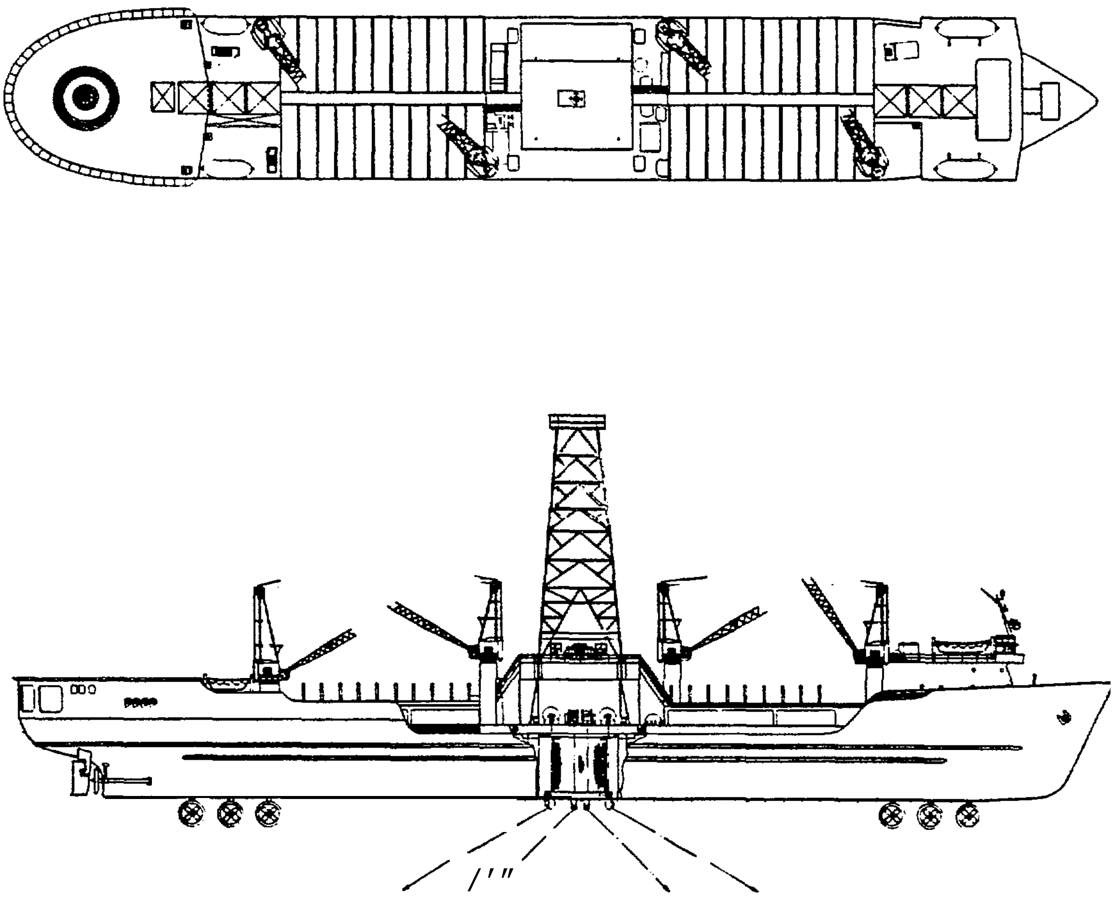

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Figure 5.1-36. Conventional Turret-moored **Drillship.**

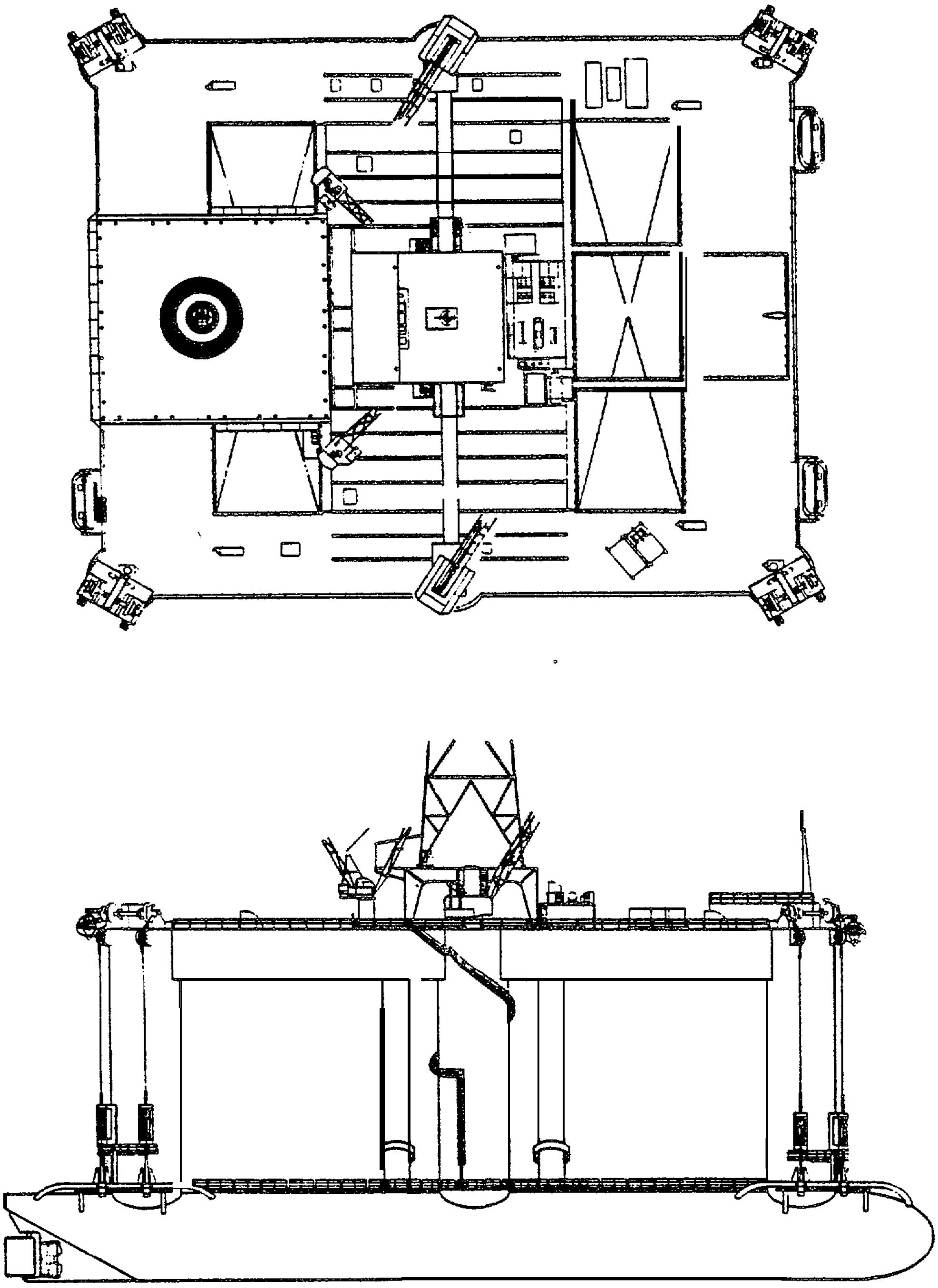

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Figure 5.1-37. Conventional Semi-submersible.

TABLE 5.1-3

## SUMMARY OF FLOATING EXPLORATION PLATFORMS

| CONCEPT NAME | FIG. NO. | PRESENT STATUS |
|---|---|---|
| Conical Drilling Unit (Kulluk) | 5,1-27 | Operational |
| Egg-shaped Ice-resistant Barge | 5.1-28 | Proposed |
| Swivel Drillship | 5.1-29 | Proposed |
| Ice-cutting Semi-submersible Drilling Vessel (ICSDV) | 5.1-30 | Detail Design |
| Arctic Drill Hull | 5.1-31 | Proposed |
| Ice-Class Semi-submersible (Ice Maiden) | 5.1-32 | Proposed |
| Ice-resistant Semi-submersible Drilling Unit | 5.1-33 | Proposed |
| Arctic Drilling Barge | 5.1-34 | Proposed |
| Round Drillship | 5.1-35 | Proposed |
| Conventional Drillship | 5.1-36 | Operational |
| Conventional Semi-submersible | 5.1-37 | Operational |

## 5.2 GENERALIZED PLATFORM CONCEPTS

In Section 5.1, numerous exploration platform concepts that have been proposed or constructed are described. These concepts are variations of three basic categories of platforms: artificial islands, bottom founded systems and floating systems, The variations that have been proposed are usually based on optimizing the concept for a particular set of conditions or circumstances. Since this study is concerned with the wide range of conditions and circumstances that may exist in the Alaskan Beaufort Sea in water depths between 20 and 90 m (65 and 300 ft), no particular proposed concept is most suitable for all scenarios.

In order to estimate exploration platform costs, and ultimately exploration and delineation well drilling costs, generalized platform concepts have been developed for each of the three basic categories. Preliminary designs for these generalized concepts have been developed and have been used as the basis for preparing cost estimates. The designs and cost estimates have been prepared as a function of the study area range of water depths. It must be borne in mind that the generalized concepts do not include the numerous variations that may be made to optimize a particular design for a particular scenario, Therefore, the costs presented may be slightly higher than the actual costs for a particular scenario. On the other hand, the generalized concepts have been designed for a specific water depth while actual exploration platforms would be designed for a range of water depths thus resulting in actual costs higher than those developed below. Because of the extreme variations in structure design, local conditions, availability of construction materials, extent of drilling program, and numerous other factors, actual costs could be expected to vary from those included in this report.

The generalized exploration platform designs and cost estimates have been based on the following conditions:

- Environmental conditions as listed in Section 3.1.
- Environmental forces calculated as described in Section 3.2.
- Unit costs for the various platform elements as described in Chapter 4.

Additional conditions applicable to a particular category of exploration platform are described in the following sections.

Based on the generalized platform costs and the costs of the various aspects of petroleum development described in Chapter 4, the cost to drill an exploration or delineation well for each of the three categories of platforms has been developed in the following three sections. The per well costs have been based on the following criteria:

- The average number of wells drilled from an artificial island or bottom founded system, at a single location, is 2.5, and this number of wells can be drilled within one year.

- A floating system can drill one well per year.
- Caissons and bottom founded structures can be used at three locations.
- Floating systems can be used for six years.
- Topsides costs are as described in Section 4.2.1 and the write-off period is assumed to be the same as that for the platform on which it is used.
- Well depth is 3,000 m (10,000 ft).
- Exploration and delineation well drilling costs are as described in Section 4.3.1.
- Ancillary vessel requirements and costs are as described in Section 4.4.2 and a 10 year write-off period is assumed.
- Support camp costs are as described in Section 4.5.3 and a 10 year write-off period is assumed.

The per well cost for exploration and delineation wells within the study area has been developed in Section 5.3 by determining the lowest per well cost for each of the drilling platform categories in each water depth. The total manpower required for the lowest cost exploration drilling operation is also presented in Section 5.3.

Preliminary designs and cost estimates for two generalized artificial island concepts have been developed: Sacrificial Beach Island and Caisson Retained Island. Note that the Sacrificial Beach

Island concept was selected over the Gravel Island concept because of the probable unavailability of a source of gravel borrow within an economical distance from the project site.

### 5.2.1 Artificial Islands

#### a) Sacrificial Beach Island

The generalized Sacrificial Beach Island (SBI) concept used for the preliminary design and cost estimates is shown in Figure 5.2-1. The cost of the concept, as a function of water depth, excluding the topsides equipment, is shown in Figure 5.2-2 for three different sand fill haul distances: 0 km, 5 km and 10 km. The cost estimates are based on the following assumptions:

- Approximately 2 m (6.5 ft) of unsuitable seabed material will be removed by dredging.
- Unit cost of stripping unsuitable material: As per Figure 4.1-4.
- Type of granular fill material: fine to medium sand.
- Unit cost of granular fill: as per Figures 4.1-2 and 4.1-3.
- Water depth at borrow site: equal to water depth at island site.
- Number of work days per season: 50.

Based on the generalized SBI costs shown in Figure 5.2-2 and the

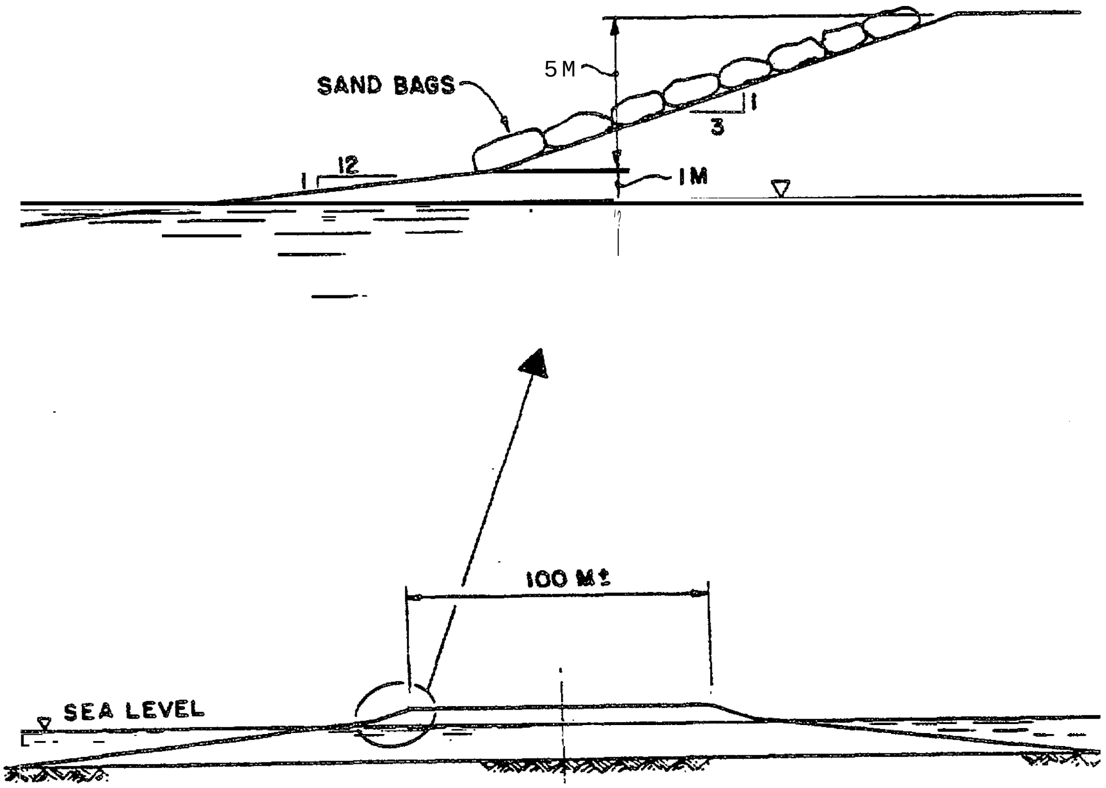

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Figure 5.2-1. Generalized Sacrificial Beach Island exploration platform.

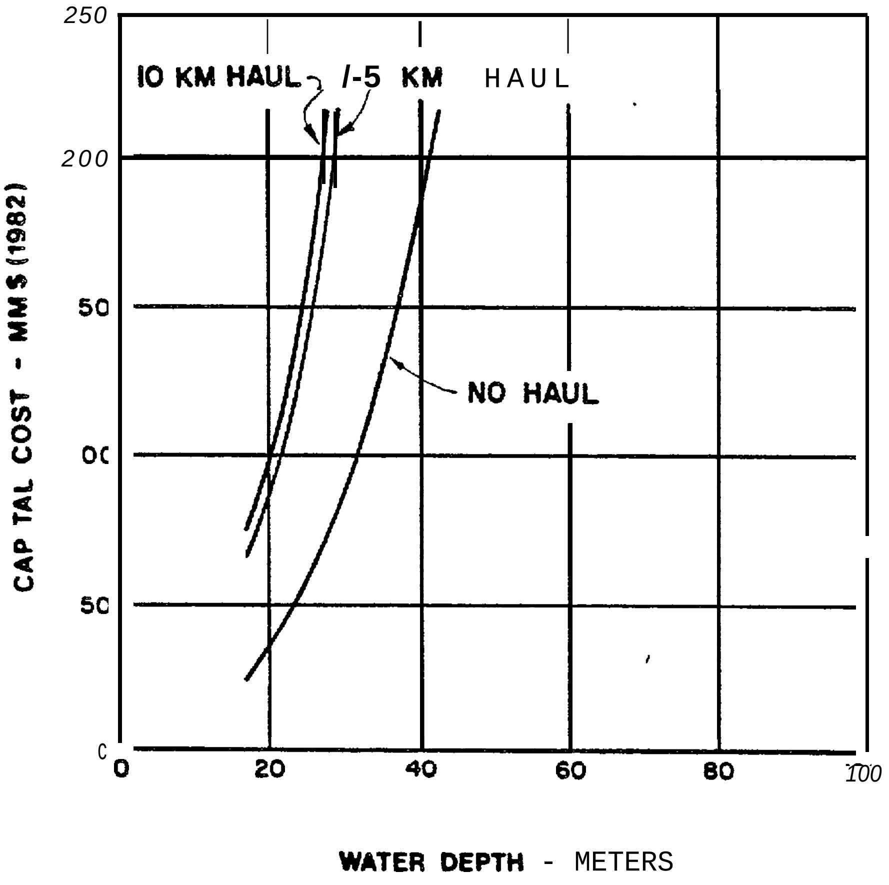

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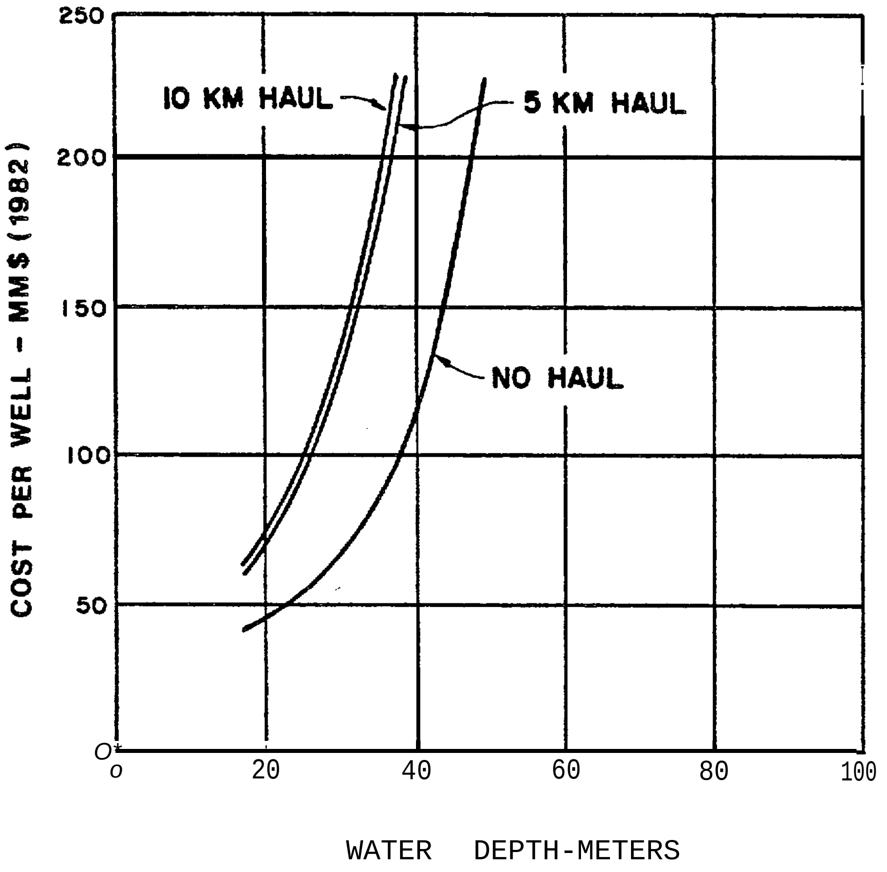
Figure 5.2-2. Generalized Sacrificial Beach Island exploration platform capital cost versus water depth.

criteria described in Section 5.2, the per well costs have been developed and are presented in Figure 5.2-3.

b) Caisson Retained Island

The generalized Caisson Retained Island (CRI) concept used for the preliminary design and cost estimates is shown in Figure 5.2-4. It is based on the CRI concept described in Section 5.1.1. It features six, prefabricated steel caissons set on top of a fine to medium sand berm and the volume contained within the ring of caissons filled with the same material. The cost of the concept, excluding the topsides equipment, as a function of water depth, is shown in Figure 5.2-5 for three different sand fill haul distances: 0 km, 5 km and 10 km. These costs are based on the lowest cost combination of caisson height versus berm height, assuming the cost of the caissons is spread over three sites. The cost estimates are also based on the following assumptions:

- Approximately 2 m (6.5 ft) of unsuitable seabed material will be removed by dredging.
- Unit cost of stripping unsuitable material: as per Figure 4.1-4.
- Type of granular fill: fine to medium sand.
- Unit cost of granular fill: as per Figures 4.1-2 and 4.1-3.
- Water depth at borrow site: equal to water depth at island site.



COST BASED ON 3000M DEEP NELL

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Figure 5.2-3. Generalized Sacrificial Beach Island exploration platform per well cost versus water depth.

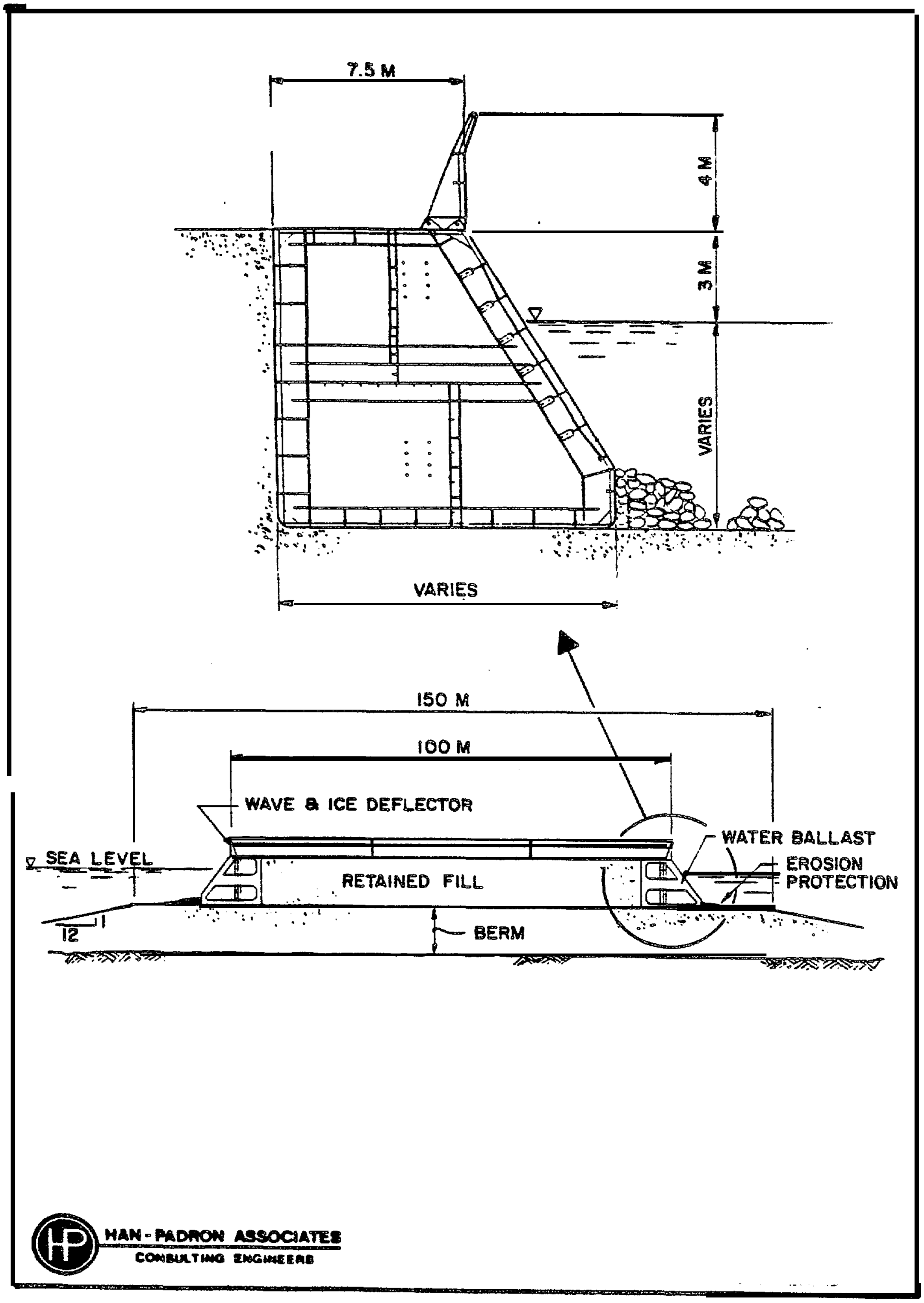

**Figure 5.2-4.** Generalized Caisson Retained Island exploration platform.

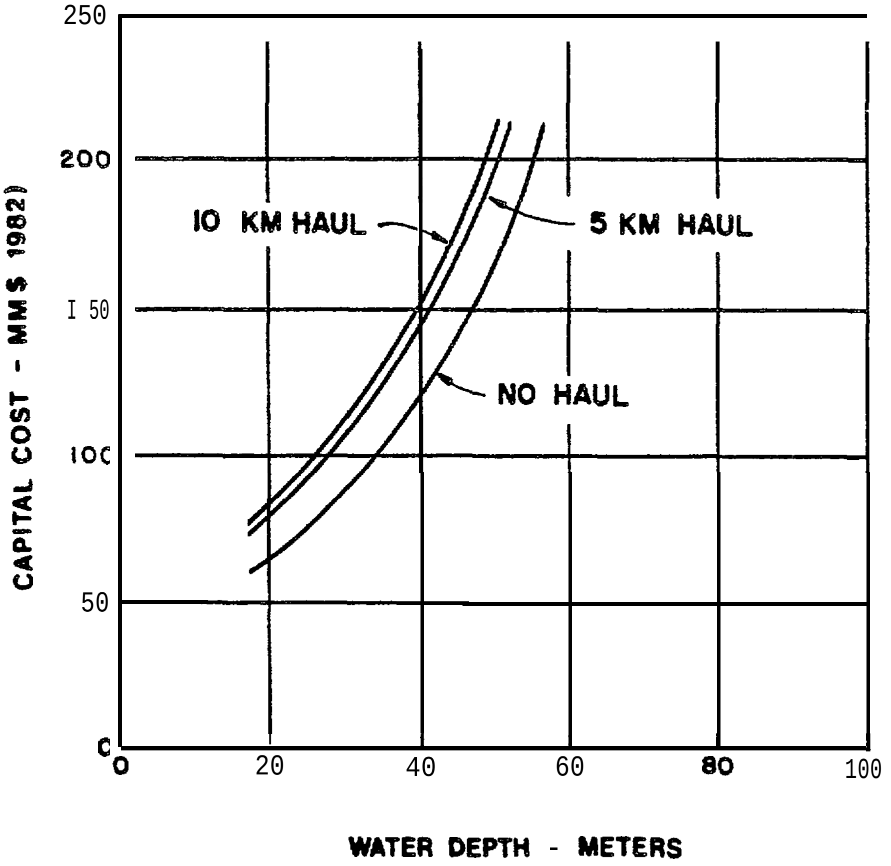

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Figure 5.2-5. Generalized Caisson Retained Island exploration platform Capital cost versus water depth - one caisson use.

- Number of work days per season: 50.
- Caisson fabrication location: Japan.
- Unit cost of caisson steel fabrication: $2,500 per tonne.
- Initial towing and installation cost: $25,000,000.

Unlike the SBI, which is used at only one location and then abandoned, a portion of the CRI (the caissons) can be salvaged and reused. For cost comparison purposes, it has been assumed that the caissons will be used three times. They can actually be used more than three times if properly maintained, but drilling contractors are generally not willing to make commitments greater than three years. Therefore, it has been assumed the caissons will be used only three times. The average cost of a CRI exploration platform, as a function of water depth, is shown in Figure 5.2-6, assuming that the caissons are used three times. In addition to the assumptions listed above, these costs are based on the assumption that the cost to relocate the caissons from one island site to another is $20,000,000.

Based on the generalized CRI costs shown in Figure 5.2-6 and the criteria described in Section 5.2, the per well costs have been developed and are presented in Figure 5.2-7. These costs include an annual cost to maintain the caissons of $3,000,000.

### 5.2.2 Bottom Founded Systems

Preliminary designs and cost estimates for a generalized,

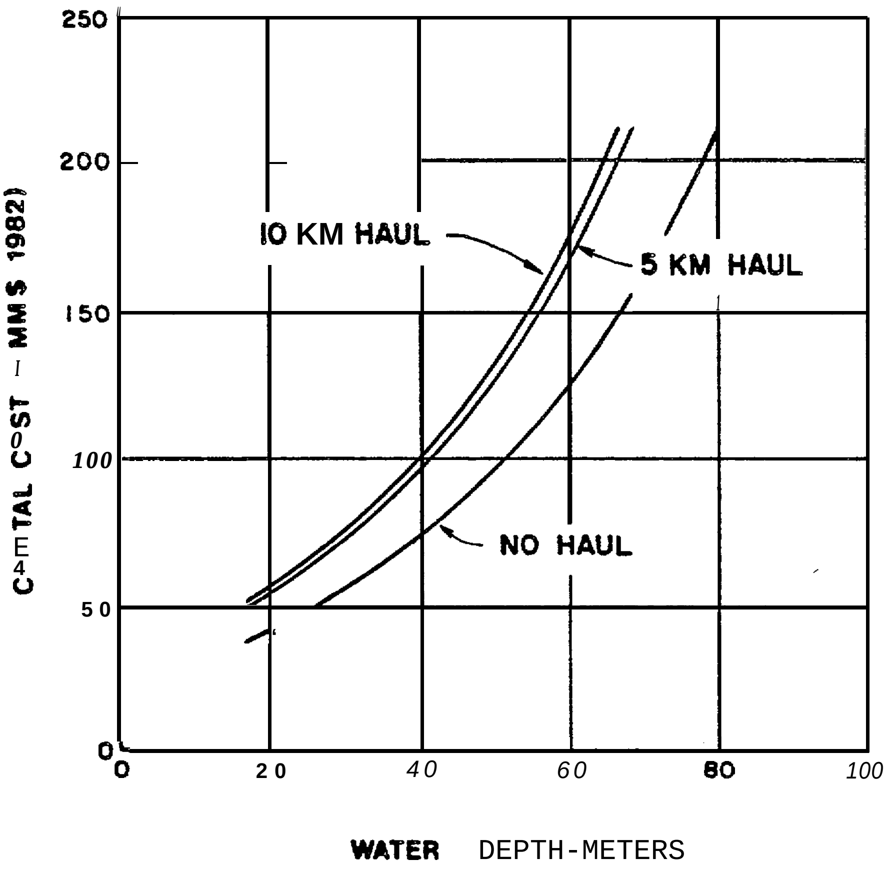

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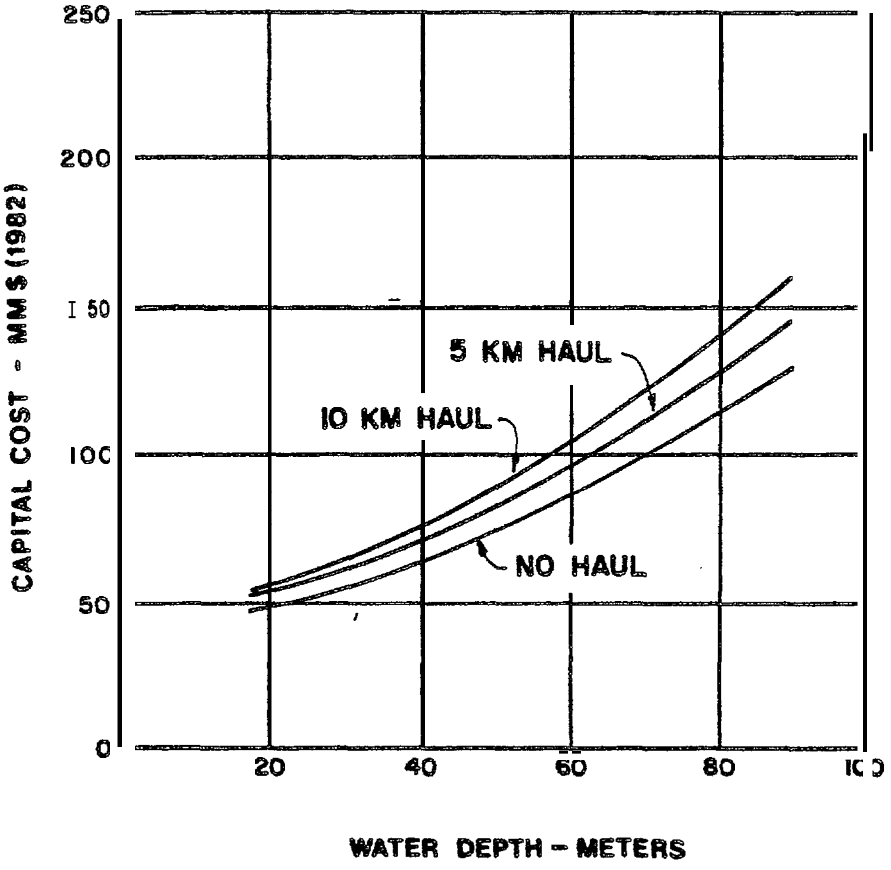
Figure 5.2-6. Average generalized Caisson Retained Island exploration platform per use capital cost versus water depth - three caisson uses.



COST BASED ON 3000M DEEP WELL

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**Figure 5.2-7.** Generalized **Caisson** Retained **Island** exploration platform per well **cost** versus water **depth.**

prefabricated bottom founded exploration platform concept have been developed. The concept, referred to as a Conical Drilling Structure (CDS), is illustrated in Figure 5.2-8. The preliminary design has been based on satisfying the following conditions:

- The horizontal component of the design ice force is approximately 132 MN (30,000,000 lb).
- The exterior surface of the structure in contact with the ice is subject to a pressure of 10,300 kPa (1,500 psi) on an area of 1 $m^2$ (10 $ft^2$) decreasing linearly to a pressure of 1,400 kPa (200 psi) on an area of 100 $m^2$ (1,000 $ft^2$).
- Approximately 5 m (16 ft) of unsuitable seabed material will be removed. by dredging and replaced with sand.
- Maximum towing draft of 8 m (26 ft). This condition led to the selection of an all steel design. However, various combinations of steel and concrete materials could also be used without significantly affecting the cost estimates.
- Center well outside diameter of 15 m (50 ft).
- The structure must be stable at all times during towing and installation.
- Only seawater ballast will be used.

Based on the above conditions, the cost of the CDS concept, including the deck structure but excluding the topsides equipment, as

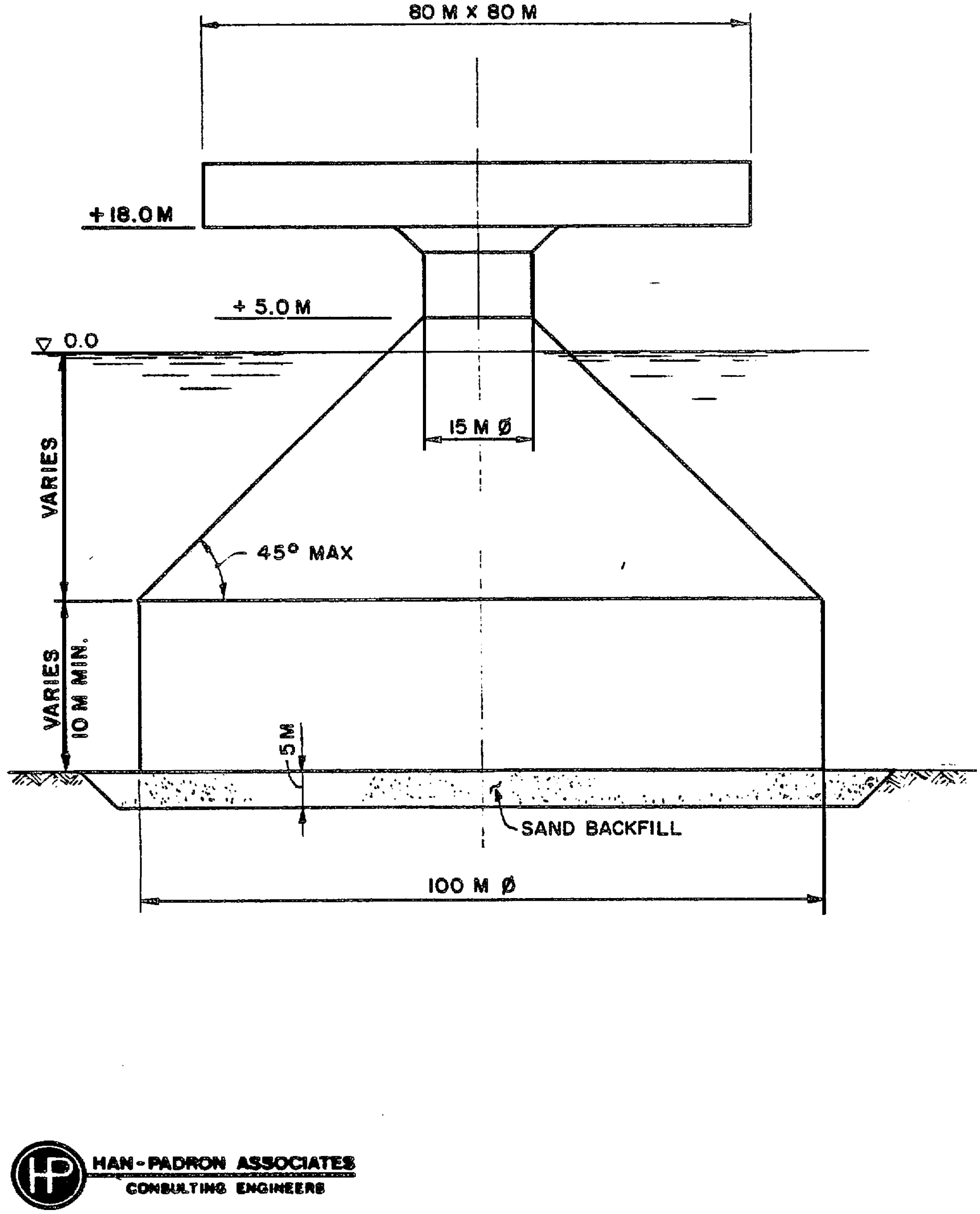

**Figure 5.2-8.** Generalized Conical **Drilling** Structure.

a function of water depth, is shown in Figure 5.2-9. The cost estimates are based on the following assumptions:

- Structure fabrication location: Japan.
- Unit cost of structure steel fabrication: $2,500 per tonne.
- Bottom preparation cost: $10,000,000 to $15,000,000 depending on water depth.
- Initial towing and installation cost: $25,000,000.

The CDS is a reusable structure. For comparison purposes it has been assumed that the structure will be used three times. Therefore, the capital cost and initial mobilization cost have been amortized over a three year period and the average cost of the platform, per location, is presented in Figure 5.2-10. In addition to the assumptions listed above, Figure 5.2-10 is based on the assumption that the cost to relocate the CDS from one site to another is approximately $20,000,000.

Based on the generalized CDS costs shown in Figure 5.2-10 and the criteria described in Section 5.2, the per well costs have been developed and are presented in Figure 5.2-11. These costs include an annual cost to maintain the CDS of $3,000,000.

### 5.2.3 Floating Systems

The generalized floating system concept is based on the Conical

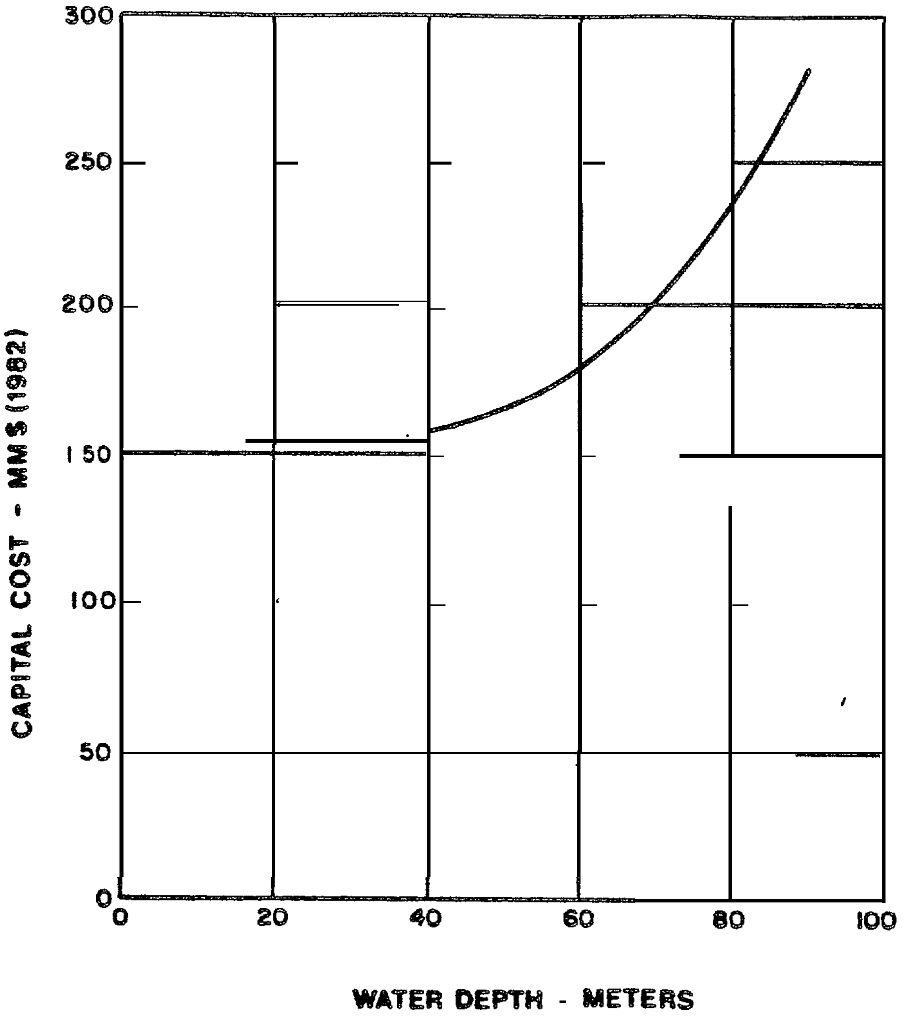

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Figure 5.2-9. Generalized Conical Drilling Structure capital cost versus water depth - one structure use.

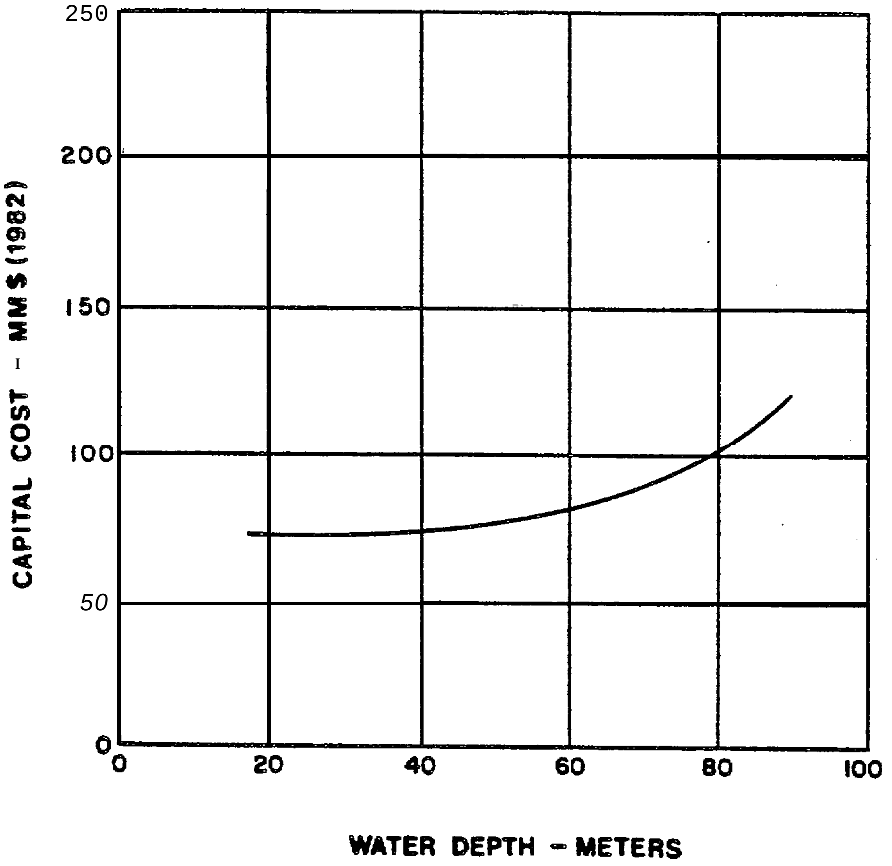

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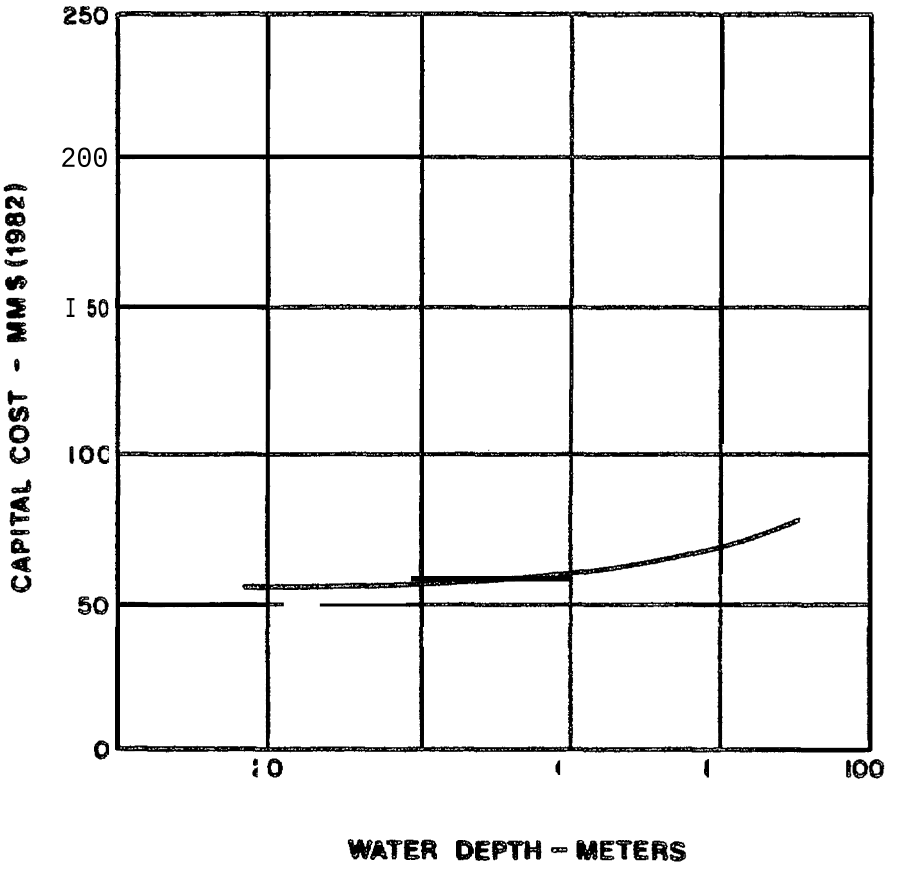
Figure 5.2-10. Average generalized Conical Drilling Structure per use capital cost versus water depth - three structure uses.



COST BASED ON 3000M DEEP WELL

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Figure 5.2-11. Generalized Conical Drilling Structure per well cost versus water depth.

Drilling Unit (CDU), Kulluk, owned and operated by BeauDril Limited, described in Section 5.1.3 and presently operating in the Canadian Beaufort Sea. The CDU, illustrated in Figure 5.1-22, was selected over conventional drillships because the open water season in the Alaskan Beaufort, during which a conventional vessel can operate, is too short to permit them to be economically feasible for an extended drilling program. It has been assumed that the generalized CDU will be designed to enable it to operate for approximately 100 days per year within the study area. The CDU cannot operate in water depths less than 30 m (100 ft).

The estimated cost of the generalized CDU has been developed from published reports of the cost of Kulluk (Lob, 1984). An allowance of 15 percent of the vessel cost has been added to account for the more severe ice conditions of the Alaskan Beaufort compared with the Canadian Beaufort and to insure that the vessel will be capable of completing one well in a season. The cost of the generalized CDU, excluding the drilling and other topsides equipment, but including the cost of the initial mobilization from Japan, is approximately $100,000,000. This cost is virtually independent of water depth for the range of water depths within the study area.

In order to develop per well drilling costs for the generalized CDU it has been assumed that the vessel will have a six year operating life. While this assumption appears to be inconsistent with the three year write-off period used for the generalized CDS and

CRI concepts, it has been used because it more closely approaches industry practice for conventional ship-shaped and semi-submersible drilling vessels. As demonstrated in Section 5.3, even the longer write-off period for the floating system does not make it economically attractive for any location within the study area for the assumed extended drilling program.

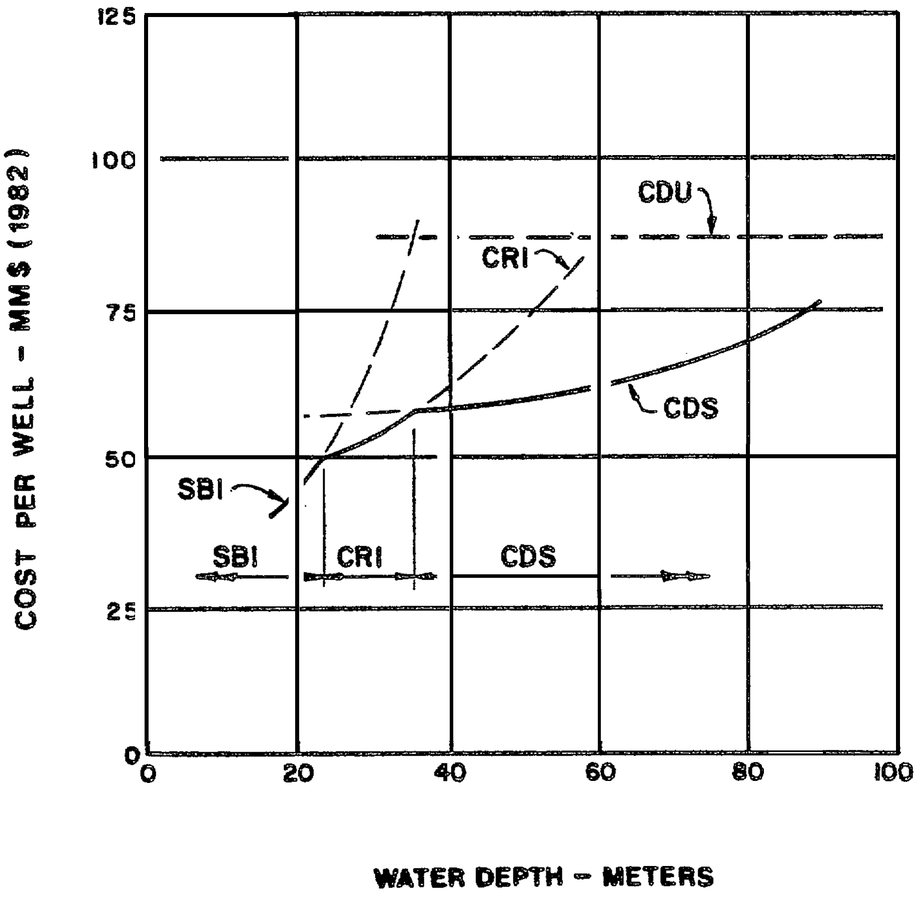
Based on the vessel cost of $100,000,000 and the criteria described in Section 5.2, the per well cost has been calculated to be $87,000,000. This cost includes an annual cost to maintain the CDU of $2,500,000.

## 5.3 EXPLORATION COSTS AND MANPOW? REQUIREMENTS

### 5.3.1 costs

In Section 5.2, the costs to drill an exploration or delineation well utilizing the three categories of exploration platforms were developed. For any particular exploration scenario, an operator will probably use the system which results in the lowest per well drilling cost . Special circumstances, of course, may dictate that a system other than the lowest per well cost system be utilized. Figure 5.3-1 illustrates the lowest per well drilling cost versus water depth, based on the assumptions described in Section 5.2 and assuming that the source of borrow material for artificial island fill is located adjacent to the exploration site. Figure 5.3-2 is similar but it is based on the assumption that the borrow source is located approximately 10 km (6 mi) from the site.

Figure 5.3-1 reveals that when the borrow source is located at the exploration site, the CRI is the most cost effective platform concept in study area water depths less than approximately 35 m (115 ft), except that in the very shallowest study area water depths the SBI is slightly more cost effective. In water depths greater than 35 m (115 ft) the CDS is the most cost effective system. When the borrow source is located approximately 10 km (6 mi) from the exploration site, the costs of the CRI and SBS are significantly increased and the CDS is the most cost effective system for the entire study



COST BASED ON 3000M DEEP WELL

SBI - Sacrificial Beach Island
CRI - Caisson Retained Island
CDS - Conical Drilling Structure
CDU - Conical Drilling Unit (floating)

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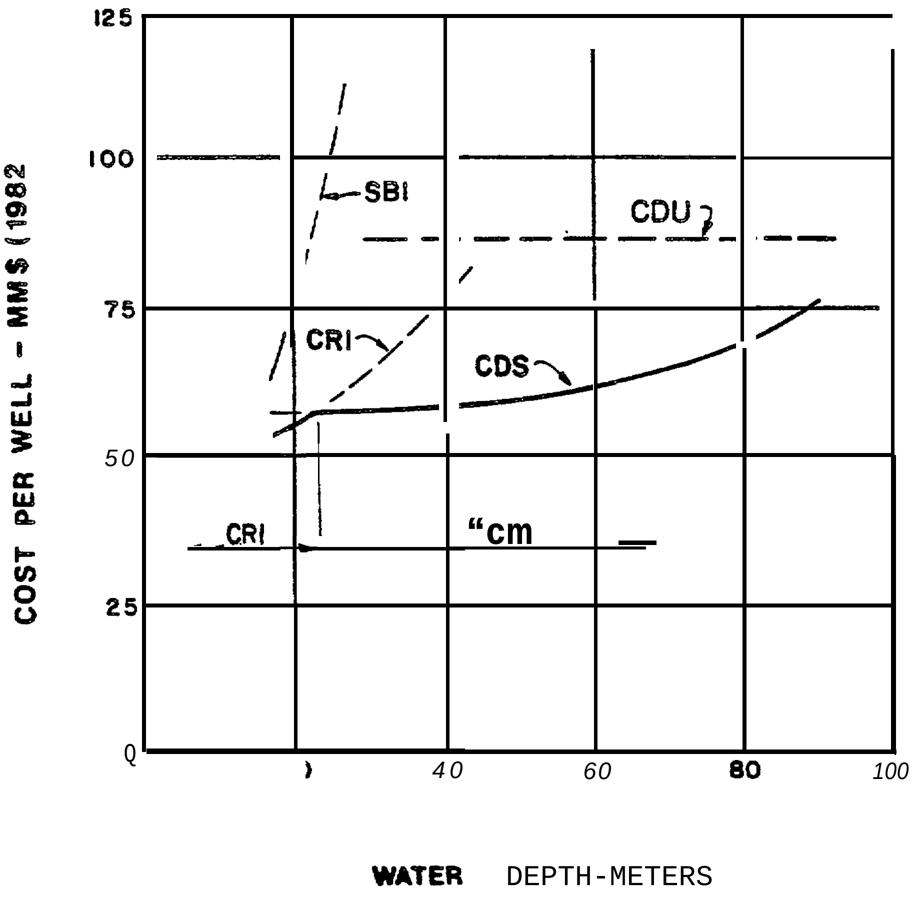
Figure 5.3-1. Per well cost versus water depth - borrow source at site.



COST BASED ON 3000M DEEP WELL

**SBI** - Sacrificial Beach Island
**CRI** - Caisson Retained Island
**CDS** - Conical Drilling Structure
CDU - Conical Drilling Unit (floating)

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**Figure** 5.3-2. per well cost versus water depth - borrow source 10 km from site.

area, except for water depths less than approximately 24 m (79 ft), where the CR I is more cost effective. The floating system is not cost effective in any water depth within the study area for the extended drilling program considered.

The per well drilling costs indicated in the figures include the following:

- The cost of the platform amortized over the average number of wells assumed to be drilled from the platform.
- The capital cost of drilling and other topsides equipment amortized over the same period of time as the exploration platforms (3 yr for artificial islands and bottom founded structures and 6 yr for floating platforms).
- The cost of drilling consumables and drilling crew.
- The capital cost of icebreaker support vessels amortized over a 10 yr period.
- The operating cost of icebreaker support vessels including crews.
- The capital cost of a base camp amortized over a 10 yr period.
- The operating cost of a base camp.

It must be borne in mind that the costs presented in Figures 5.3-1 and 5.3-2 are based on numerous criteria, conditions and assumptions as defined throughout this report. Significant changes in any of these factors could, of course, change the results.

### 5.3.2 Manpower

The manpower required during exploration activities varies depending on the type of exploration platform used and the season. Excluding construction operations, the approximate manpower requirements during drilling operations are as follows:

|  | Drilling Operations Manpower |  |  |
|---|---|---|---|
| Manpower Function | Artificial Island | Bottom Founded | Floating |
| Drilling crew | 95 | 95 | 95 |
| Icebreaker support vessel crews | 50 | 50 | 75 |
| Base camp staff | 50 | 50 | 50 |
| Total | 195 | 195 | 220 |

The drilling operations manpower for artificial islands and bottom founded structures is required year-round except when drilling is restricted to protect migrating whales. However, floating platforms will only operate approximately 100 days per year and the remainder of the year only a skeleton crew is required.

Artificial islands and bottom founded platforms require a construction crew to relocate the platform every summer season. The crew would be on site approximately two and a half months. The approximate construction manpower requirements, in addition to those required for drilling operations, are as follows:

| | Construction Operations Manpower | | |
|---|---|---|---|
| Manpower Function | Artificial Island | Bottom Founded | Floating |
| Crew on floating equipment | 90 | 50 | 0 |
| Crew on shore | 20 | 10 | 0 |
| Total | 110 | 60 | 0 |

The above construction manpower does not include the manpower required to construct the base camp, which is a one-time operation.

# 6.0 PRODUCTION TECHNOLOGY ASSESSMENT

Unlike exploration activities, crude oil production in the Beaufort Sea has yet to be carried out. Numerous production platform concepts have been proposed, but the number is considerably less than that proposed for exploration platforms. It is likely that additional concepts will be developed in the future, prior to the need to construct the first production platform in water depths exceeding 20 m (65 ft). As for exploration platforms, no absolute engineering constraint to the development of these concepts exists. However, the cost of production platforms will be considerably greater than exploration plaforms due to the requirement to stay on station for a long period of time and thus be unable to relocate to avoid extremely large ice features. Also, the space demands for production platforms are greater since oil/gas/waterseparation equipment and oil storage may be required on the structure.

## 6.1 EXISTING AND PROPOSED PLATFORM CONCEPTS

Numerous production platform concepts have appeared in the literature. The development of these concepts, particularly for water depths greater than 20m (65 ft), is less advanced than for exploration platform concepts. A number of the concepts proposed for production platforms are similar to those proposed or utilized for exploration platforms. However, the design criteria for a production platform, which must stay on location for 20 years or so, are more severe than for an exploration platform. Also, production platforms are usually considerably larger than exploration platforms. The concepts for which information has been made available, including those previously described under exploration platform concepts, are listed below. To avoid repetition, where appropriates reference is made to the exploration platform descriptions in Section 5.1 rather than repeating the descriptions. It should be borne in mind, however, that the production platforms will usually be larger and designed to withstand higher loading and may not incorporate features that enable the platform to be relocated. As for exploration platforms, not all of the concepts listed are equally viable and not all are suitable for the water depths of the study area but they have been included to provide a complete overview.

The same classification described for exploration platforms is used in this section, except that floating concepts are not considered feasible production platforms in the study area. The classifications are as follows:

- Artificial Islands
- Bottom Founded

Some concepts fall within both classifications and their assignment to a particular classification may be somewhat arbitrary.

As for the exploration platforms, the data that are provided below are based primarily on published information and the claims of the various concept creators or proponents. No attempt has been made to evaluate these claims or compare the merits of the individual concepts. The order in which the concepts are presented has no significance. Cost data for existing and proposed production platform concepts are not presented for the reasons described in Section 5.1. Cost "data are presented only for the generalized production platform concepts described in Section 6.2.

### 6.1.1 Artificial Islands

#### Gravel Island

See Section 5.1.1.

#### Sacrificial Beach Island (SBI)

See Section 5.1.1.

#### Sandbag-retained Island

See Section 5.1.1.

### Sandtube-retained Island

See Section 5.1.1.

### Necklace

See Section 5.1.1.

### Tarsiut Caisson Island

See Section 5.1.1.

### Caisson Retained Island (CRI)

See Section 5.1.1.

### Stacked Steel Caisson System

See Section 5.1.1.

### Cellular Island

See Section 5.1.1.

### Arctic Production and Loading Atoll (APLA)

The purpose of the Arctic Production and Loading Atoll (APLA) is to create a sheltered, ice-free harbor for year-round production and icebreaker tanker transportation. To do so, two submerged berms are built with two entrances to the protected area. Concrete caissons, installed at the perimeter of' the atoll are filled with sand ballast and backfilled to achieve a maximum sliding resistance. The berm is composed of seabed material dredged into place with slopes of approximately 1:5. The harbor would contain drilling and production facilities and a loading terminal for icebreaker tankers, The tankers would enter through the ports between the berms. The atoll's above water area would serve to support drilling and production facilities with storage capabilities. APLA is illustrated in Figure 6.1-1.

APLA is in the conceptual design stage. It is considered to be suitable for water depths of 60 to 75 m (200 to 250 ft) and is designed to withstand the impact of an ice feature 60 m (200 ft) thick and 8 to 15 km (5 to 9 mi) in diameter (Offshore Petroleum: A Business Opportunities Program, 1981).

### 6.1.2 Bottom Founded Systems

#### Mobile Arctic Gravity Platform

See Section 5.1.2.

#### Arctic Mobile Drilling Structure (AMDS)

See Section 5.1.2.

#### Mobile Gravity Platform (Monotone)

See Section 5.1.2.

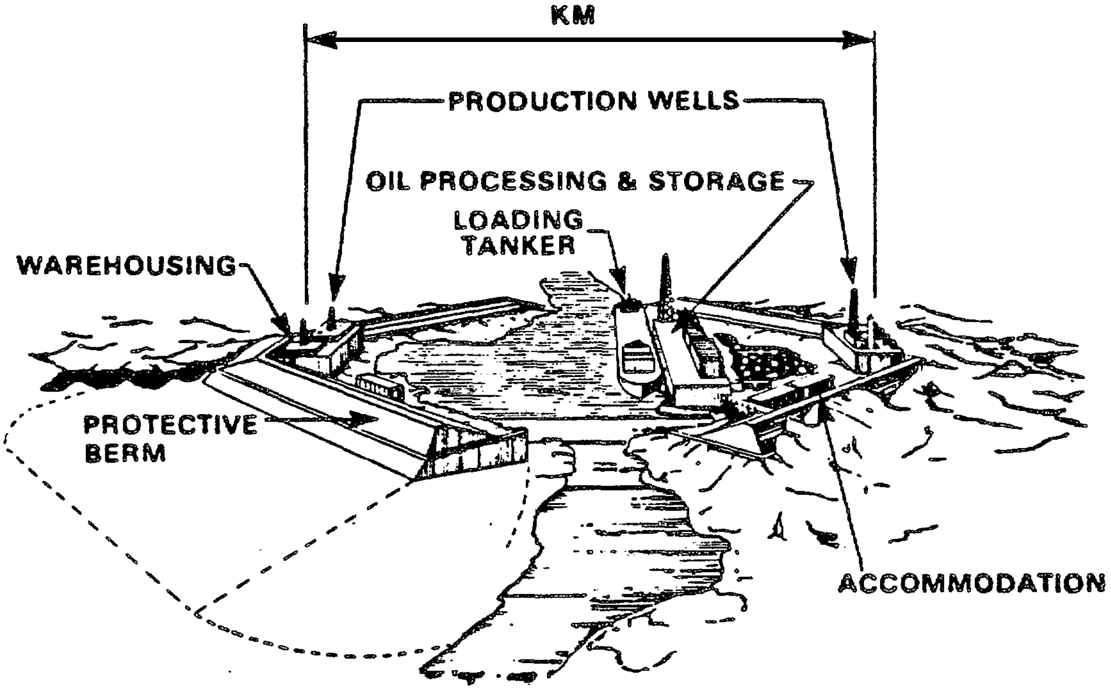

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Figure 6.1-1. Arctic Production and Loading Atoll (APLA).

Single Steel Drilling Caisson (SSDC)

See Section 5.1.2.

Mobile Arctic Island (MAI)

See Section 5.1.2.

Sonat Hybrid Arctic Drilling Structure (SHADS)

See Section 5.1.2.

Conical Monopod

See Section 5.1.2.

Arctic Drilling Structure With Detachable Caisson Mat

See Section 5.1.2.

Arctic Composite Platform (ARCOP)

See Section 5.1.2.

Concrete Production Island

The Concrete Production Island is being considered for use in the Beaufort Sea in water depths of 12 to 55 m (40 to 180 ft). The unit, illustrated in Figure 6.1-2, is in the conceptual design stage.

Once placed on location, the six-sided concrete caisson structure would be filled with dredged sand or gravel to secure it to the seabed. Like gravel islands, it would provide a solid base for

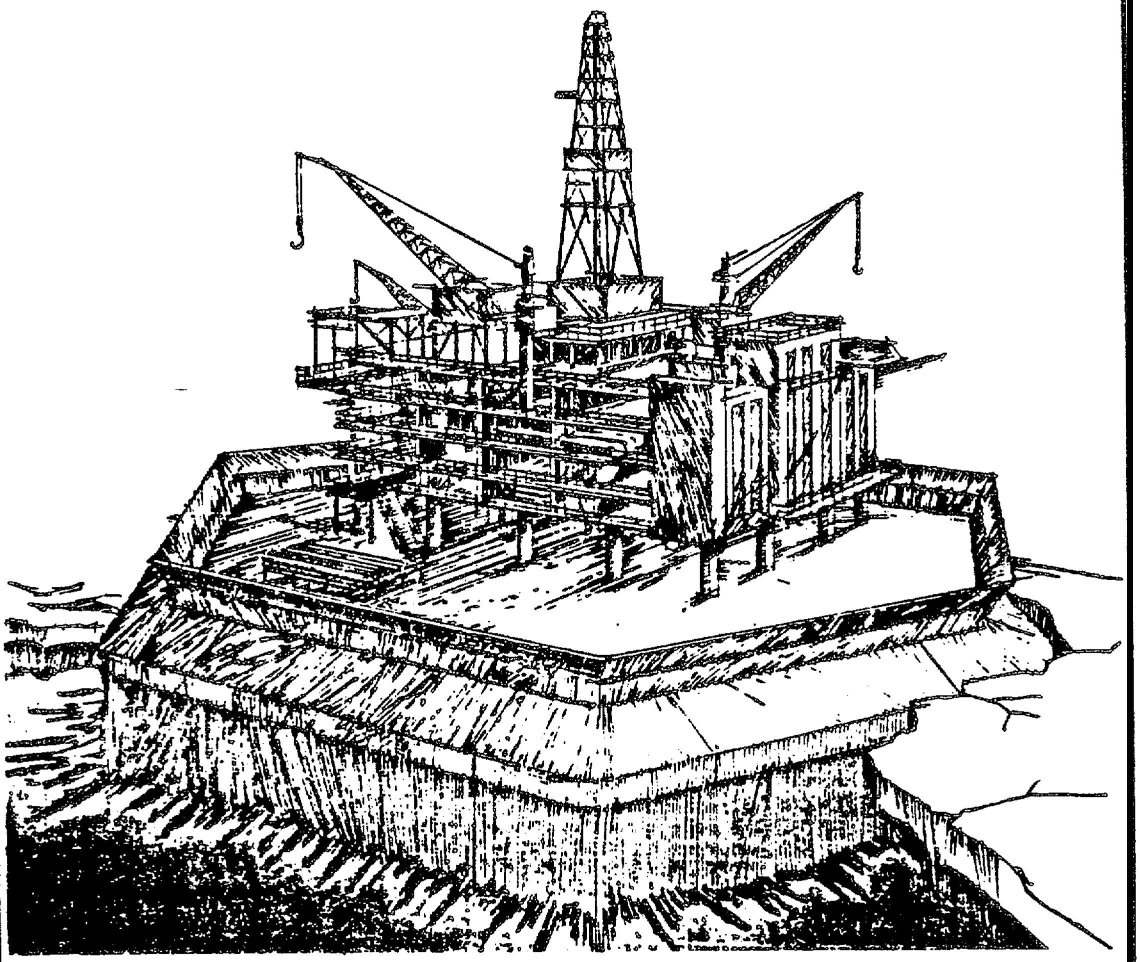

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Figure 6.1-2. Concrete Production Island.

drilling and production systems in an ice environment. As presently conceived the Concrete Production Island is sized for a production rate of up to 300,000 BPD (Lamp, 1982).

### Arctic Production Monotone (APM)

The Arctic Production Monotone (APM) has been designed for year-round operation in the shear zone of the Beaufort Sea, in water depths up to 75 m (250 ft). APM is illustrated in Figure 6.1-3. Forty wells at 1.8 m (6 ft.) centers can be accommodated with a riser angle of less than one degree. A production rate of 120,000 BPD was used in the preliminary design. The platform is comprised of a" doughnut-shaped base, a bottle-shaped superstructure and a removable jack-up deck." The conical mid-section fails ice in flexure, while the cylindrical shaft fails it in crushing. The main distinguishable feature of the concept is the possibility of disconnecting the midsection and deck from the base (due to the system of anchor pins) when an ice island approaches. First, barge-shaped deck halves are lowered into the water, then the mid-section is freed by removing the locking wedge dogs from the slots in the pins. The base is left in place to protect the wellheads. APM is designed as a gravity structure in overconsolidated clays and may be a piled structure in soft clays.

APM is in the preliminary design stage. The governing design ice load is a 35 m (115 ft) multiyear ridge frozen into a 3 m (10 ft)

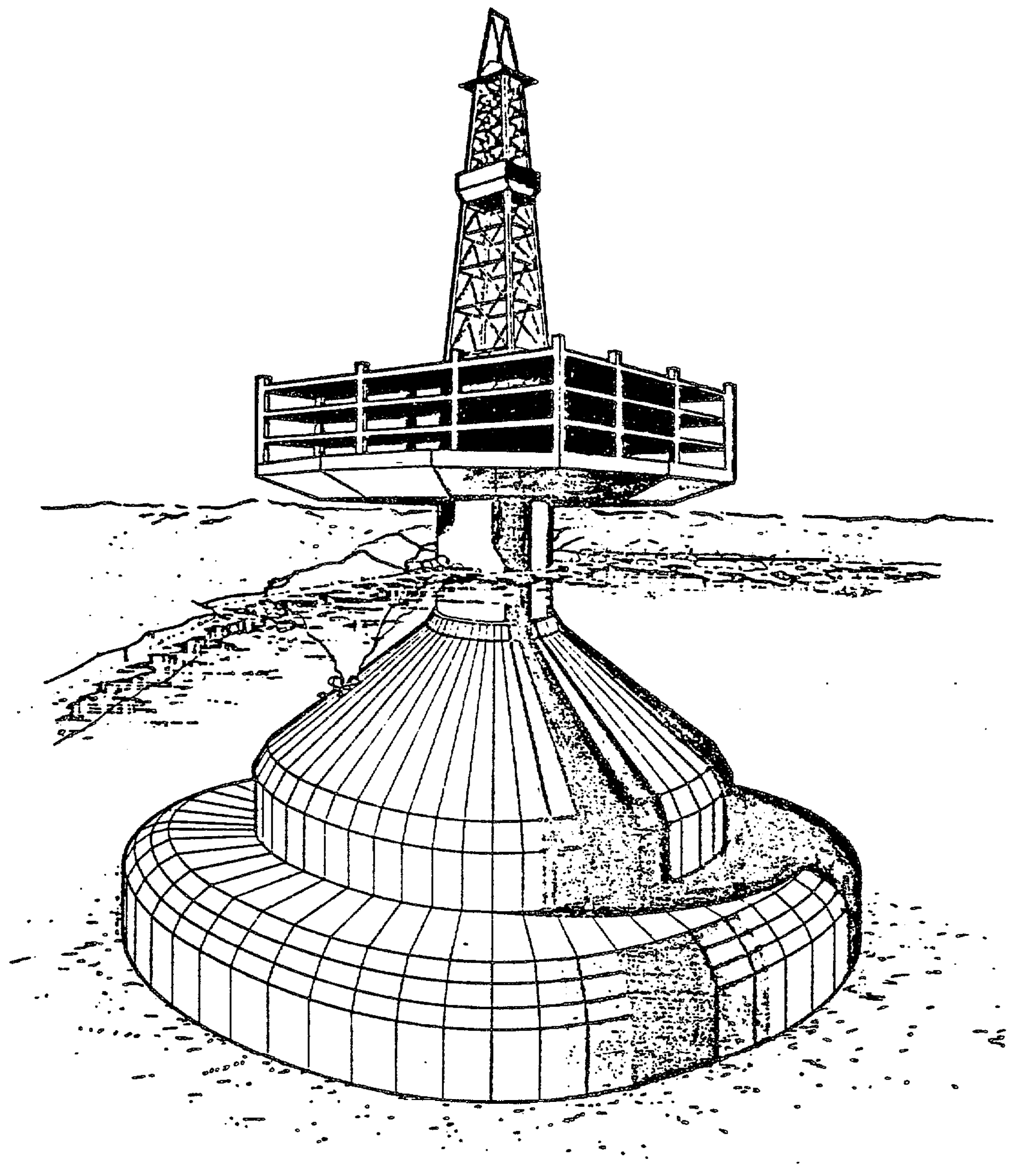

Figure 6.1-3. Arctic Production Monotone (APM).

thick multiyear ice sheet. However, further work is required in the optimization of the design as it relates to ice loads and operational requirements (Stenning and Schumann, 1979).

## Deepwater Actively Frozen Seabed Structure (DAFS)

The Deepwater Actively Frozen Seabed Structure (OAFS), illustrated in Figure 6.1-4, is suitable for water depths ranging from approximately 25 m (82 ft) to 50 m (164 ft) or more. A conceptual design has been developed for a water depth of 30 m (100 ft), based on a production rate of 200,000 BPD. Storage space for more than 1,000,000 barrels of crude oil is available within the structure. The DAFS production structure concept consists of a large, octagonal, steel caisson. The structure is ballasted only with seawater, and is anchored to the seabed by a gridwork of vertical shear plates and a system of thermal piles. The structure's ability to withstand horizontal forces due to ice and wave action is derived from the embedment of the shear plates and the lateral resistance of the thermal piles combined with the increase in strength of the seabed soil through freezing.

Due to the fact that DAFS relies on the frozen seabed soil mass for its stability, it is relatively lightweight and suitable for installation on virtually any seabed soil conditions that may be encountered. Since it does not require ballast other than seawater, it can be completely installed in a matter of weeks and can be

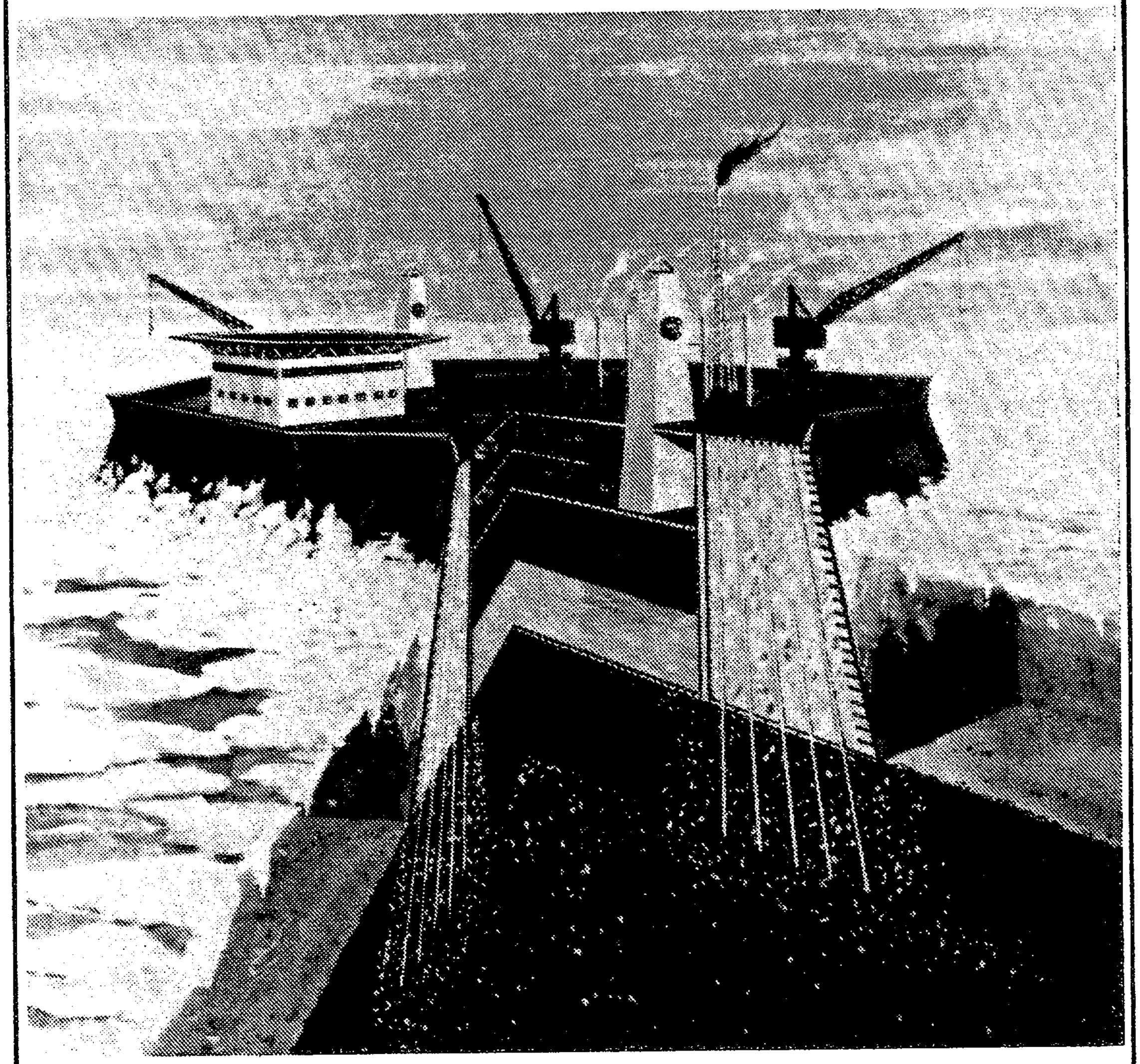

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**Figure 6.1-4.** Deepwater Actively **Frozen** Seabed Structure **(DAFS).**

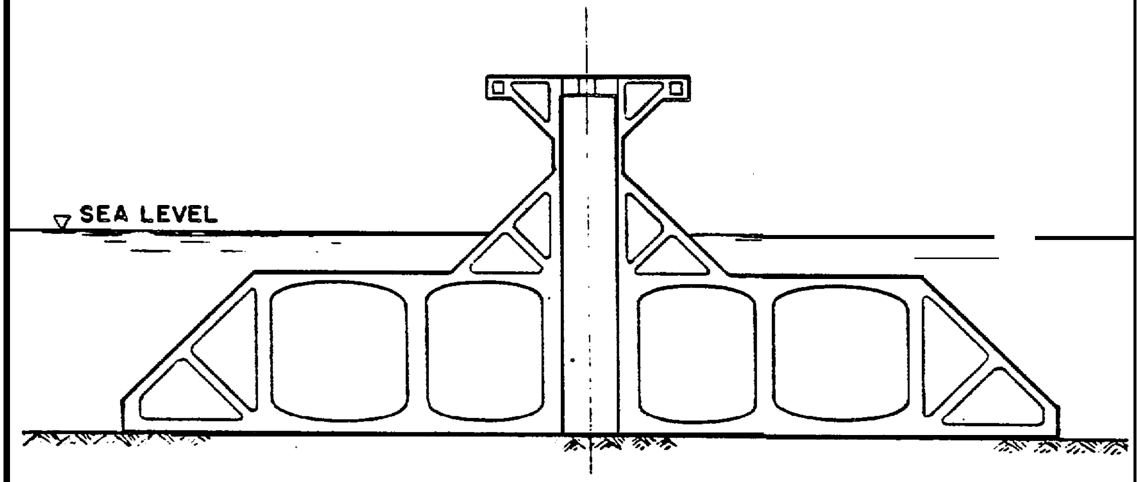

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Figure 6.1-5. Concrete Conica Production/Storage Structure.

relocated if necessary (Padron et al., 1984).

## Concrete Conical Production/Storage Structure

The Concrete Conical Production/Storage Structure, illustrated in Figure 6.1-5, is essentially a cone on top of a massive base and is to be made of prestressed concrete. The base is composed of a series of prestressed concrete cylinders which serve as storage compartments and also provide structural redundancy. Voids between the cylinders are water or sand filled. The base is cone-shaped to allow the ride-up of ice features. The midsection is also conical and has a friction-reducing coating to ensure the failure of ice in bending. The deck structure is of an inverted cone cantilevered type. The shape of the upper section provides protection from ice ride-up.

The Concrete Conical Production/Storage Structure is in the conceptual design stage. The initial design is for a water depth of 46 m (150 ft), and the critical ice loading condition is a pressure ridge with a maximum keel depth of 24 m (80 ft). The structure has a storage capacity of 2.8 million bbl (Offshore Petroleum. A Business Opportunities Program, April 1981).

## Controlled Stiffness Steel Arctic Cone (COSSAC)

The Controlled Stiffness Steel Arctic Cone (COSSAC) was designed

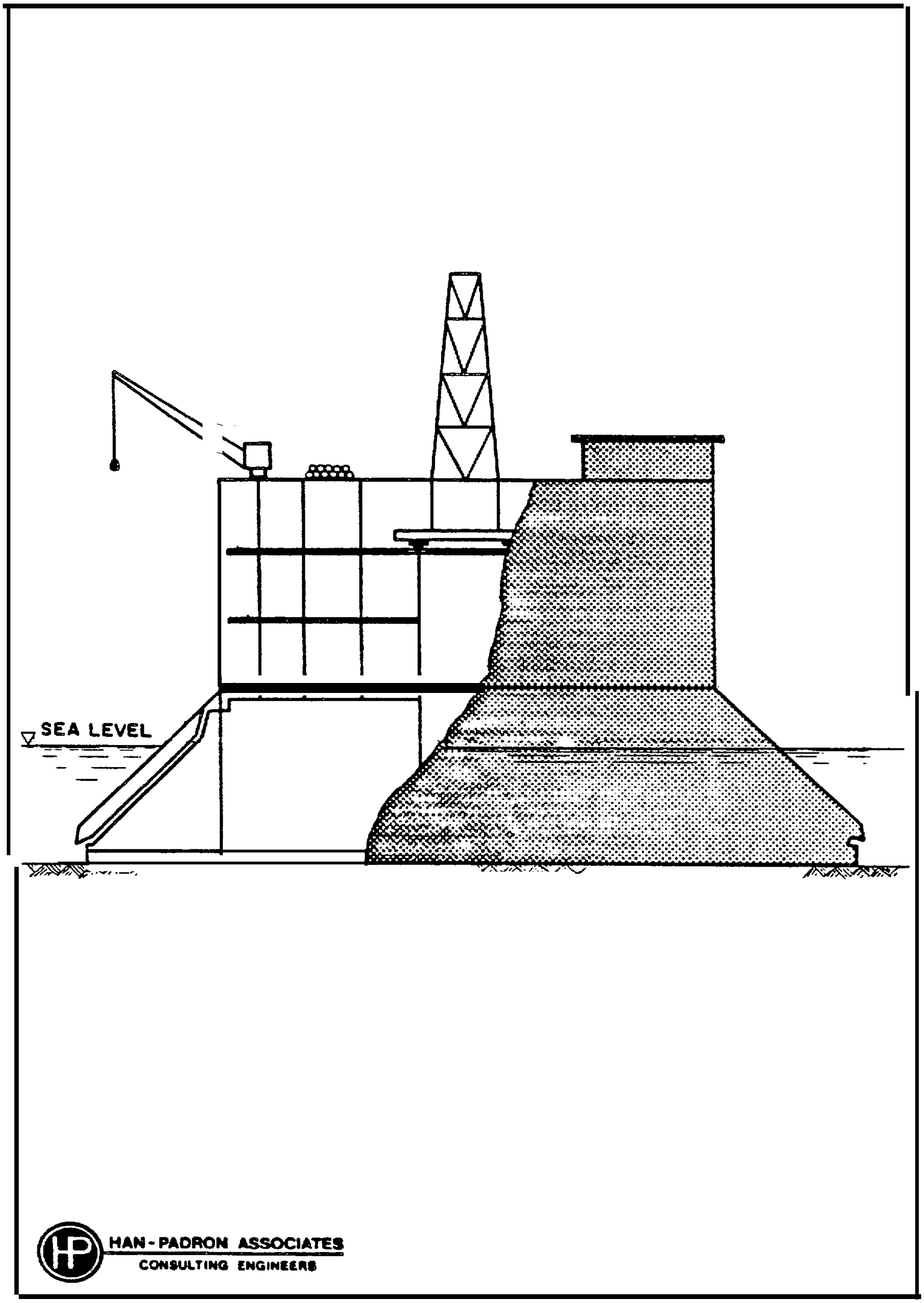

Figure 6.1-6. Controlled Stiffness Steel Arctic Cone (COSSAC).

based on controlling the relative stiffnesses of the primary structural members to distribute the concentrated load effects from multiyear ice features. The conceptis in the preliminary design stage and appears feasible for shallow areas of the Beaufort Sea. The preliminary design was based on a water depth of 14 m (45 ft). COSSAC is illustrated in Figure 6.1-6. It consists of an upper cylindrical portion sitting on the frustrum of a 45° cone. The structure is designed as a completely enclosed and totally integrated system. The production facilities are housed on three deck levels within the upper cylinder. The structure is held on location by water ballast. The conical portion is the primary ice defense system. It it comprised of an outer shell supported by beams which span between radial and circumferential bulkheads. The outer shell does not directly contact the bulkheads, therefore the entire cone is suspended from the top. This system also helps to reduce temperature stresses.

The present COSSAC design is based on a production rate of 60,000 BPD. In addition, a 60 well slot configuration and two drilling rigs were assumed in the design. The design also assumed that COSSAC will be constructed in a dry dock and towed to the site. However, at the present time, there is no suitable dry dock on the west coast of the U.S. (Boaz and Bhula, 1981).

### Fixed Ice-resistant Platform With Integrated Deck

The Fixed Ice-resistant Platform with Integrated Deck, illustrated in Figure 6.1-7, is a fixed offshore platform concept for the shallow, coastal waters of the Beaufort Sea. The present design, which is at the preliminary stage, is capable of operating in 9 to 18 m (30 to 60 ft) of water and is intended for a production rate of 150,000 barrels of oil per day from up to 38 wells.

The substructure consists of four conical legs extending from interconnected cylindrical bases. It can be either of a gravity or gravity-plus-piled type depending on soil conditions. A conical leg section is used below the depth reached by an ice sheet having maximum thickness. This configuration is designed to fail thick ice in flexure. In the depth region of the natural ice sheet formation, where adfreeze may occur, a cylindrical leg is used to limit the area exposed to ice pressure. The shell of the cone and cylinder consists of an outer and inner steel skin with radial webs and is filled with reinforced concrete. The structure has been designed for a maximum wave height of 12 m (40 ft), and a tide range of 3 m (9 ft). A local ice pressure of up to 7 mPa (1,000 psi) over a 0.3 $m^2$ (1 $ft^2$) area of leg surface has been considered. A 5 m (16 ft) thick ice sheet, acting on all four legs simultaneously, which is quite unlikely to occur in the land-fast zone, was used for the overall design of the structure. Seabed soils are assumed to consist mainly of overconsolidated clays and fine-grained sand or silt. Sliding resistance is obtained by the use of 3.3 m (11 ft) deep skirts, however, several alternatives, including battered piles, can be used in the case of

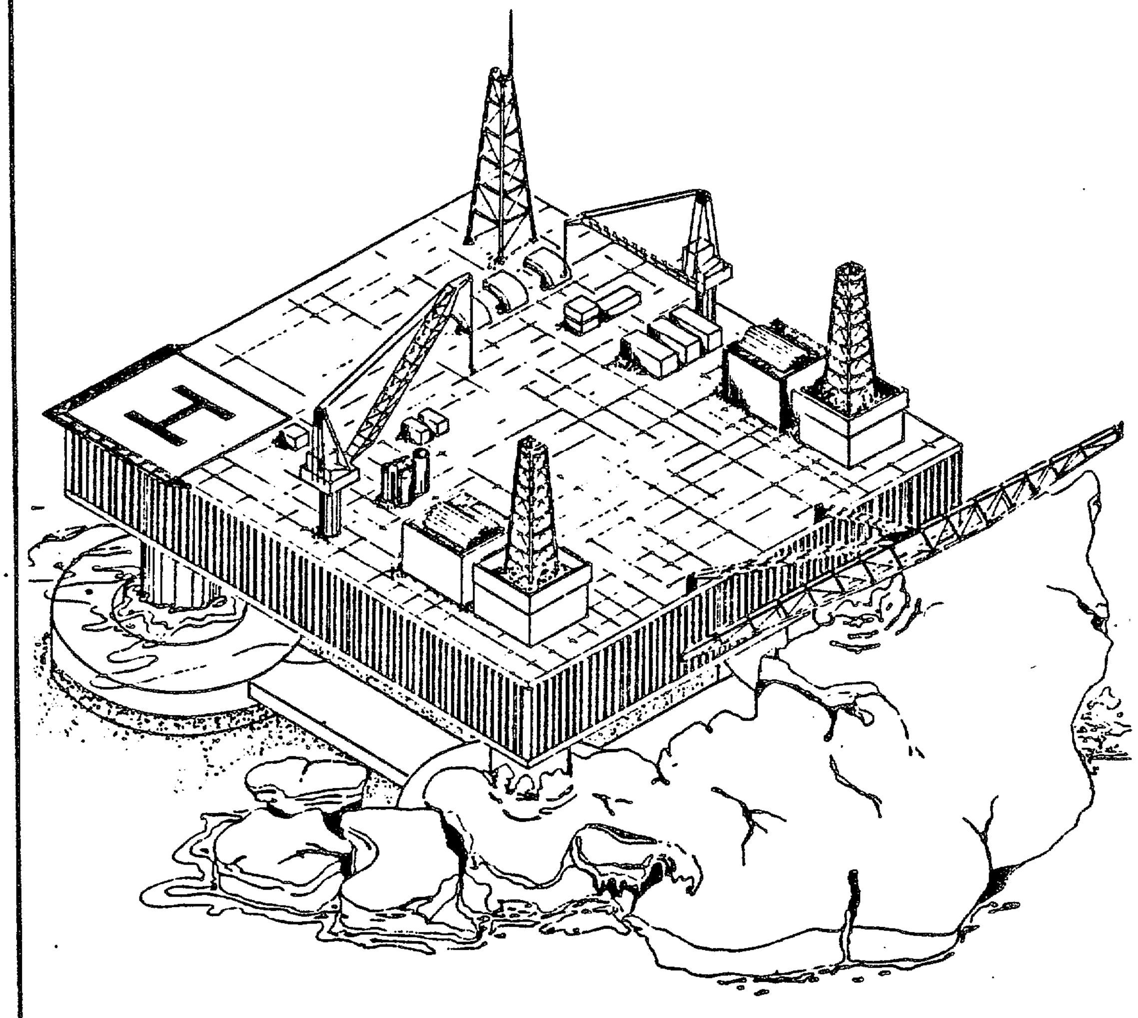

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Figure 6.1-7. Fixed Ice-resistant Platform with Integrated Deck.

less favorable soil conditions (Kleiwer and Forbes, 1980).

## Concrete Island Production System (CIPS)

The Concrete Island Production System (CIPS), illustrated in Figure 6.1-8, is a large gravity structure which is suitable for use as a long term, fixed development drilling and production platform, The concept, which is based on the modular CIDS technology (see Section 5.1.2), has already been developed beyond the feasibility stage. It is assembled from flotable modular elements, and the draft of each element can be limited to 7.5 m (25 ft) for transit to the assembly site.

The basic design philosphy of the CIPS is to provide a simple, massive, gravity platform that can resist the design ice forces without movement relative to the seabed. A design goal is to minimize the amount of construction and installation activity that would be required at the installation site. Thus, the baseline CIPS consists of a steel base, two regular octagon concrete bricks, and three deck storage barges which are installed on top of the bricks. The drilling, production and quarters modules are installed on the barges in the shipyard. The entire unit is assembled in a deep water area. Seawater is used for ballast during the stacking and final installation operations. The baseline CIPS incorporates 60 well slots, two development drilling rigs, quarters for 300 men, and two enclosed decks.

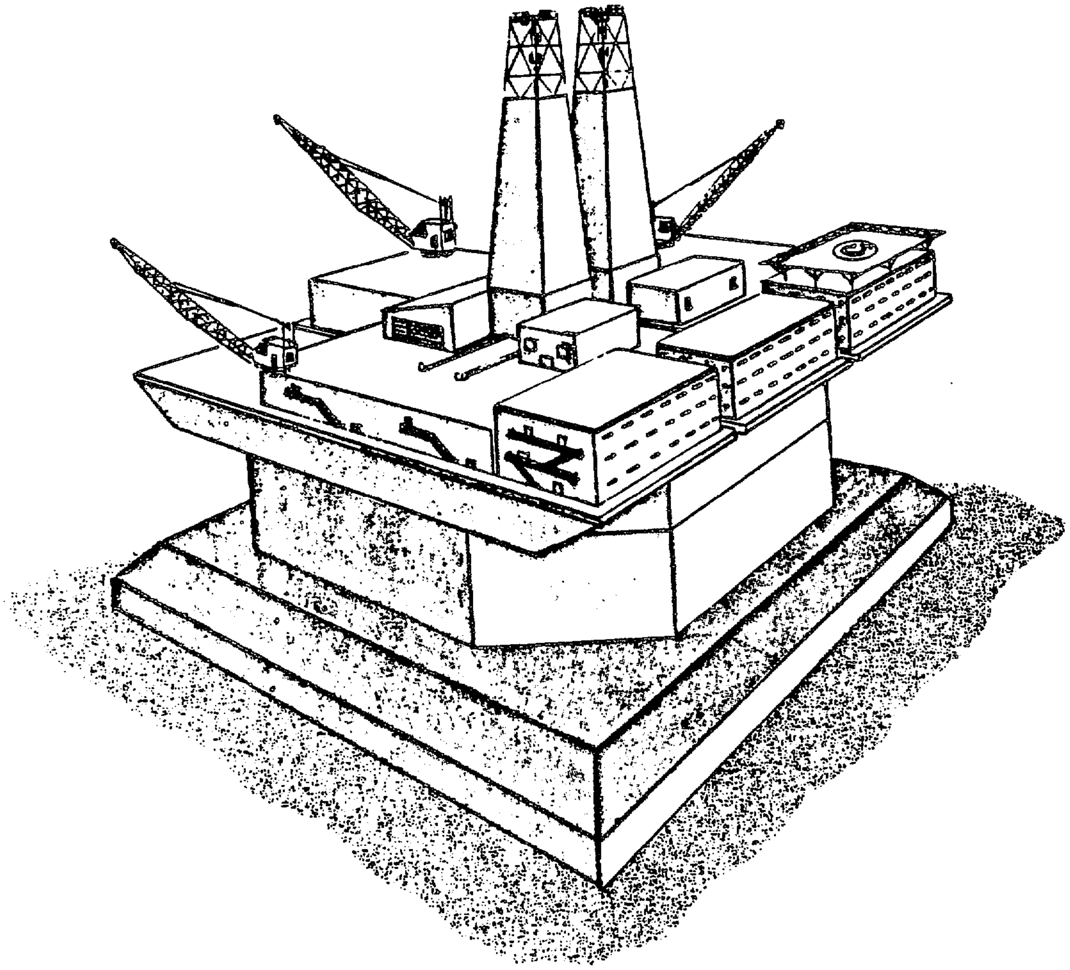

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Figure 6.1-8. Concrete Island Production System(CIPS).

The CIPS is designed for installation in water depths up to 30 m (100 ft), however, the concept could be extended to deeper water. The unit is capable of operating in the shear ice zone. The limiting design condition is the sliding of the foundation under the extreme ice loads, and the consequent foundation preparation required. Such preparation may include cement injection or excavation and backfill. In either case a sand or gravel pad is necessary to assure adequate coupling between the base and soil (Person, 1984).

## Recoverable Arctic Platform (RAP)

The Recoverable Arctic Platform (RAP) is a bottom founded production structure designed for operation in the transition zone of the Beaufort Sea. RAP is illustrated in Figure 6.1-9. The platform is composed of an upper conical steel structure resting on a large disk shaped concrete base. The unique feature of this concept is the possibility of removing the upper steel cone in the event of an imminent collision with an ice island, and towing it to a safe area. This is accomplished by means of a sealing/suction system at the interface with the base, allowing very fast disconnection of the upper cone. The production facilities are located inside the steel cone, which is stable in the towing mode. Wellheads and manifold are enclosed in a chamber located inside the concrete base and are thus protected against ice impact after the removal of the upper cone.

RAP is in the conceptual design stage. The design has been developed based on a 200,000 BPD production rate and a 30 m (100 ft) water depth. However, the general concept has potential applicability to deeper water depths (Gieca, 1984).

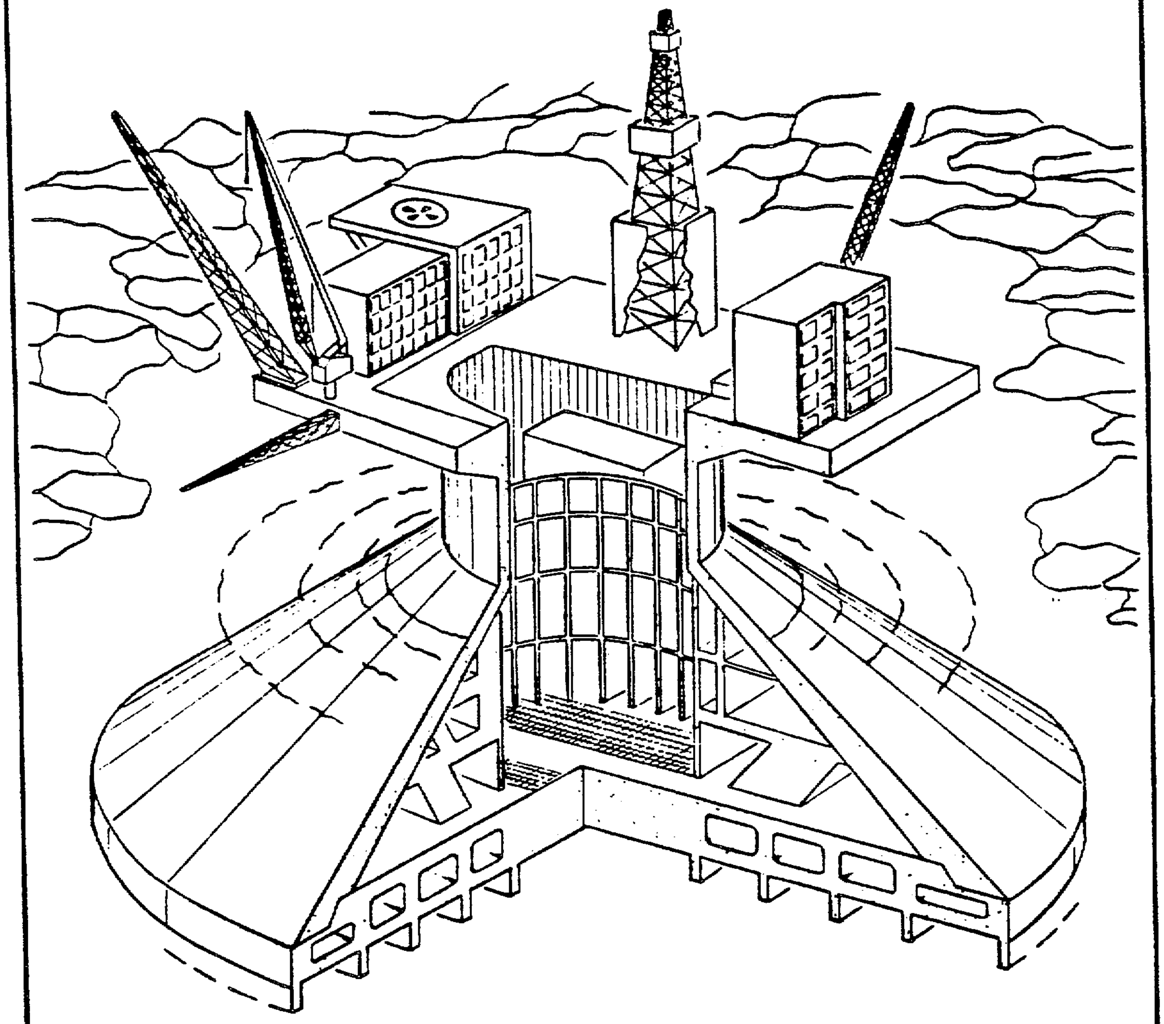

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Figure 6.1-9. Recoverable Arctic Platform (RAP

## 6.2 GENERALIZED PLATFORM CONCEPTS

In Section 6.1, numerous proposed production platform concepts are described. These concepts are variations of artificial islands and bottom founded systems and are based on differing design criteria. In order to estimate production platform costs, generalized platform concepts have been developed for each category. Preliminary designs for these generalized concepts have been developed and have been used as the basis for preparing cost estimates. It must be borne in mind that the generalized concepts do not include the numerous variations that may be made to optimize a particular design for a particular scenario. As for the generalized exploration platform concepts, extreme variations in structure design, local conditions, availability of construction materials, and numerous other factors, may result in actual costs that vary substantially from those included in this report.

The generalized production platform designs and cost estimates have been based on the following conditions:

- Environmental conditions as listed in Section 3.1.
- Environmental forces calculated as described in Section 3.2.
- Unit costs for the various platform elements as described in Chapter 4.

Additional conditions applicable to a particular category of production platform are described in the following sections.

### 6.2.1 Artificial Islands

Preliminary designs and cost estimates for a generalized Caisson Retained Island have been prepared. A Sacrificial Beach Island was not considered as a production platform because of the permanent nature of the platform and the extensive annual maintenance that would be required on a SBI. A Gravel Island was not considered because of the probable unavailability of a source of gravel borrow within an economical distance from the project site.

The generalized Caisson Retained Island (CRI) concept is shown in Figure 6.2-1. It is based on the CRI concept described in Section 5.1.1. It features six prefabricated steel caissons set on top of a fine to medium sand berm and the volume contained within the ring of caissons filled with the same material. The cost of the concept, including the topsides equipment as a function of water depth for sand fill haul distances of 0 km and 10 km and for production rates of 100,000, 200,000 and 300,000 BPD, is shown in Figure 6.2-2. These costs are based on the lowest cost combination of caisson height versus berm height. The cost estimates are also based on the following assumptions:

- Approximately 2 m (6.5 ft) of unsuitable seabed material will be removed by dredging.
- Unit cost of stripping unsuitable material: as per Figure 4.1-4.

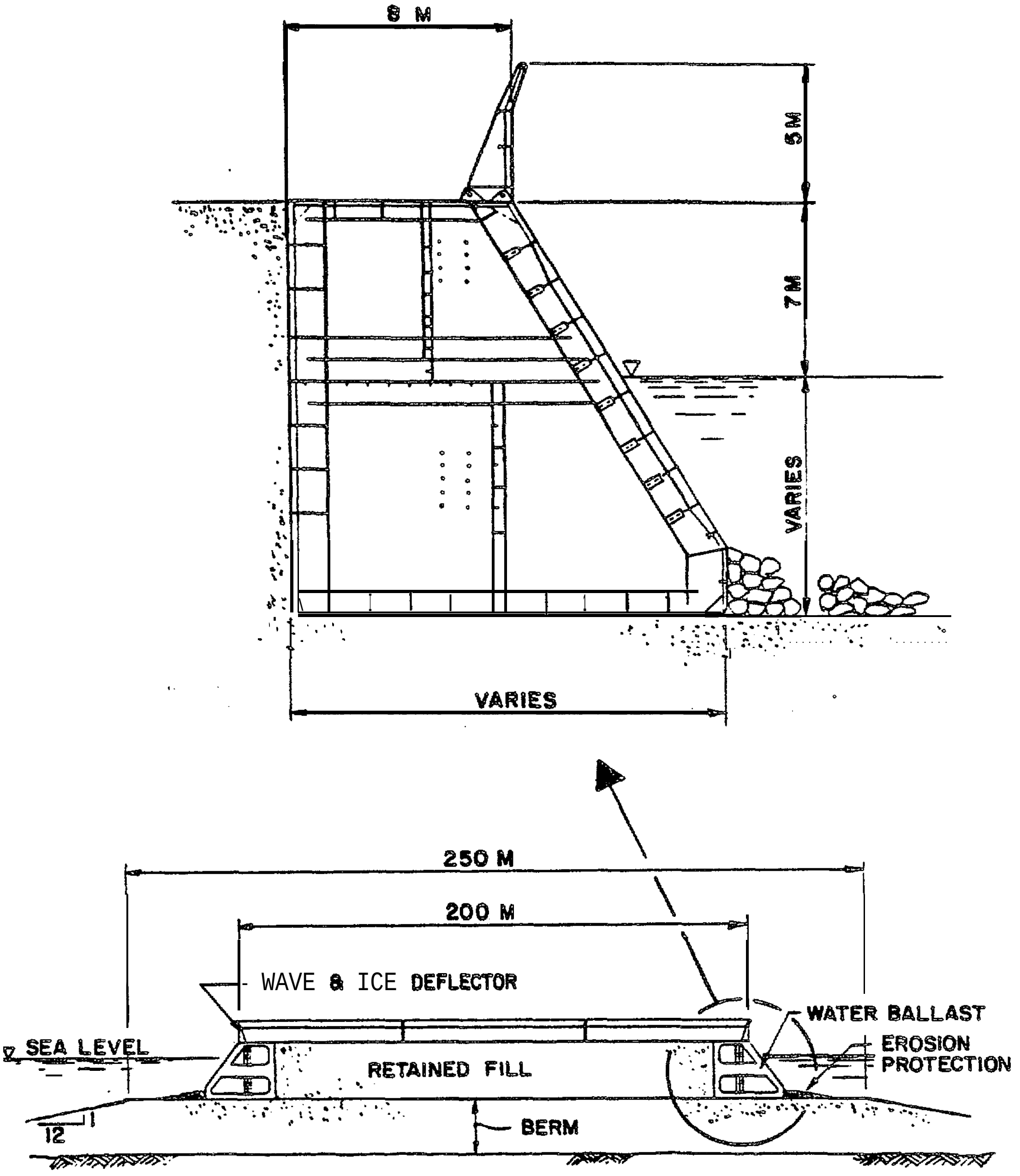

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Figure 6.2-1. Generalized Caisson Retained Island production platform.

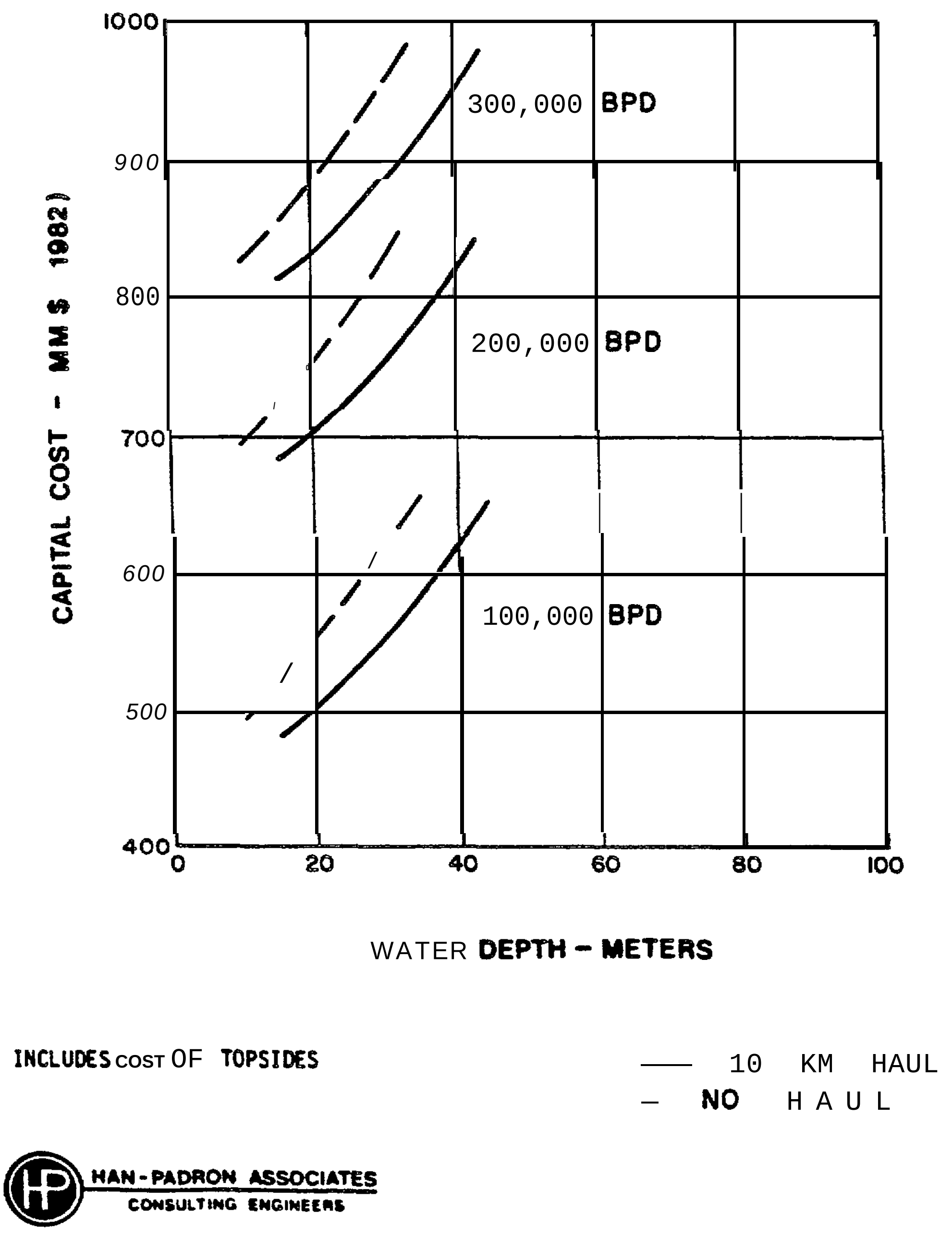

Figure 6.2-2. Generalized Caisson Retained Island production platform capital cost versus water depth.

- Type of granular fill: fine to medium sand.
- Unit cost of granular fill: as per Figures 4.1-2 and 4.1-3.
- Water depth at borrow site: equal to water depth at island site.
- Number of work days per season: 50
- Caisson fabrication location: Japan
- Unit cost of caisson steel fabrication: $2,500 per tonne.
- Towing and Installation cost: $25,000,000.
- Cost of topsides: as per Table 4.2-5.

### 6.2.2 Bottom Founded Systems

Preliminary designs and cost estimates for a generalized prefabricated bottom founded production platform concept have been developed. The concept, referred to as a Conical Production Structure (CPS), is similar to the Conical Drilling Structure (CDS) and is 'illustrated in Figure 6.2-3. The preliminary design has been based on satisfying the following conditions:

- The horizontal component of the design ice force is approximately 470 MN (106,000,000 lb).
- The exterior surface of the structure in contact with the ice is subject to a pressure of 10,300 kPa (1,500 psi) on an area of 1 $m^2$ (10 $ft^2$) decreasing linearly to a pressure of 1,400 kPa (200 psi) on an area of 100 $m^2$ (1,000 $ft^2$) .

- Approximately 8 m (26 ft) of unsuitable seabed material will be removed by dredging and replaced with sand.
- Maximum towing draft of 8 m (26 ft). This condition led to the selection of an all steel design. However, various combinations of steel and concrete materials could also be used without significantly affecting the cost estimates,
- Center well outside diameter of 25 m (82 ft) to provide space for 68 conductors.
- The structure must be stable at all times during towing and installation.
- A combination of sand and seawater ballast will be used.

Based on the above conditions, the cost of the CPS concept, including the deck structure and topsides equipment, as a function of water depth and for production rates of 100,000, 200,000 and 300,000 BPD, is shown in Figure 6.2-4. The cost estimates are based on the following assumptions:

- Structure fabrication location: Japan
- Unit cost of structure steel fabrication: $2,500 per tonne
- Bottom preparation cost: $12,000,000 to $18,000,000 depending on water depth
- Towing and installation cost: $30,000,000
- Cost of topsides: as per Table 4.2-6.

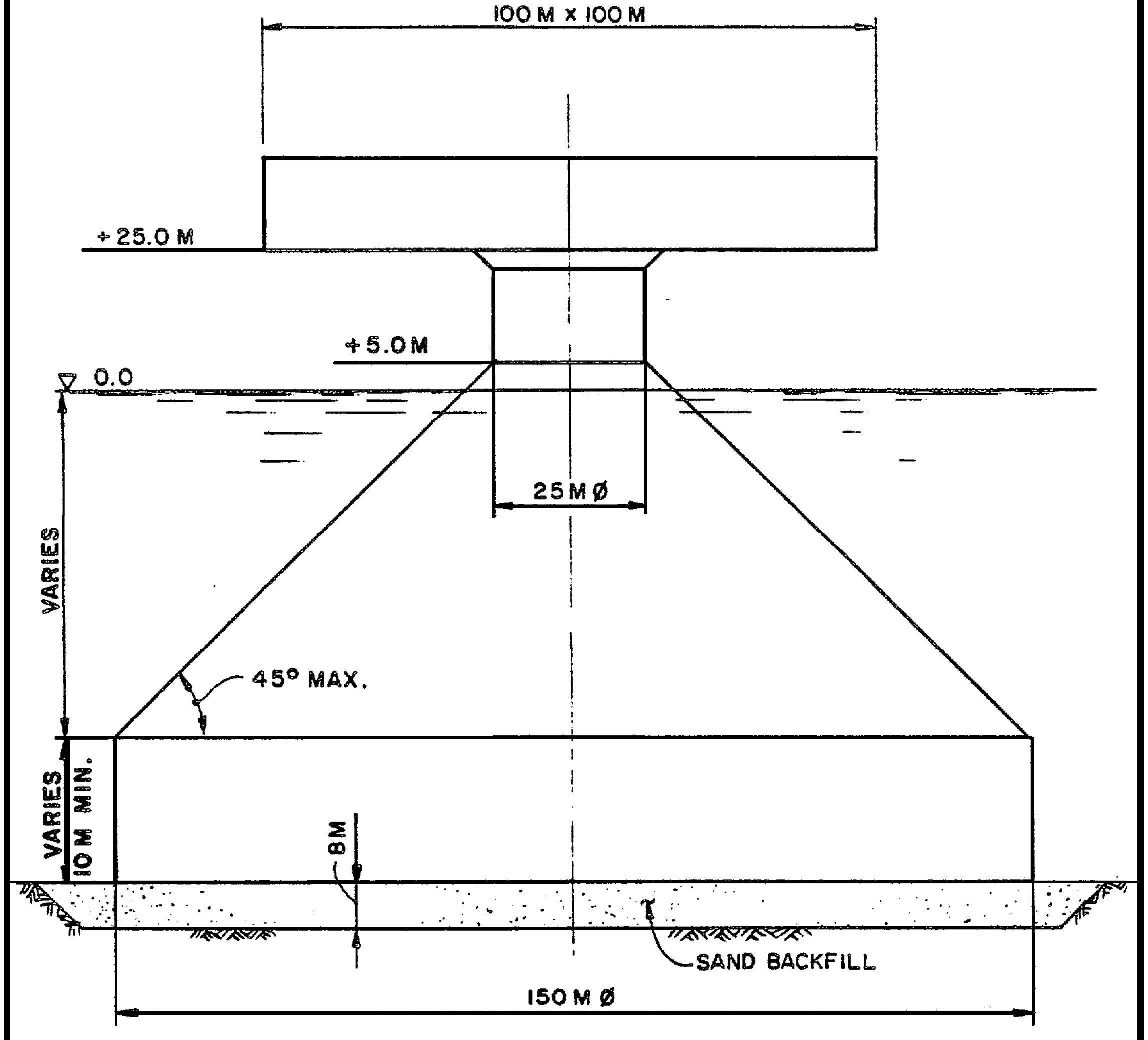

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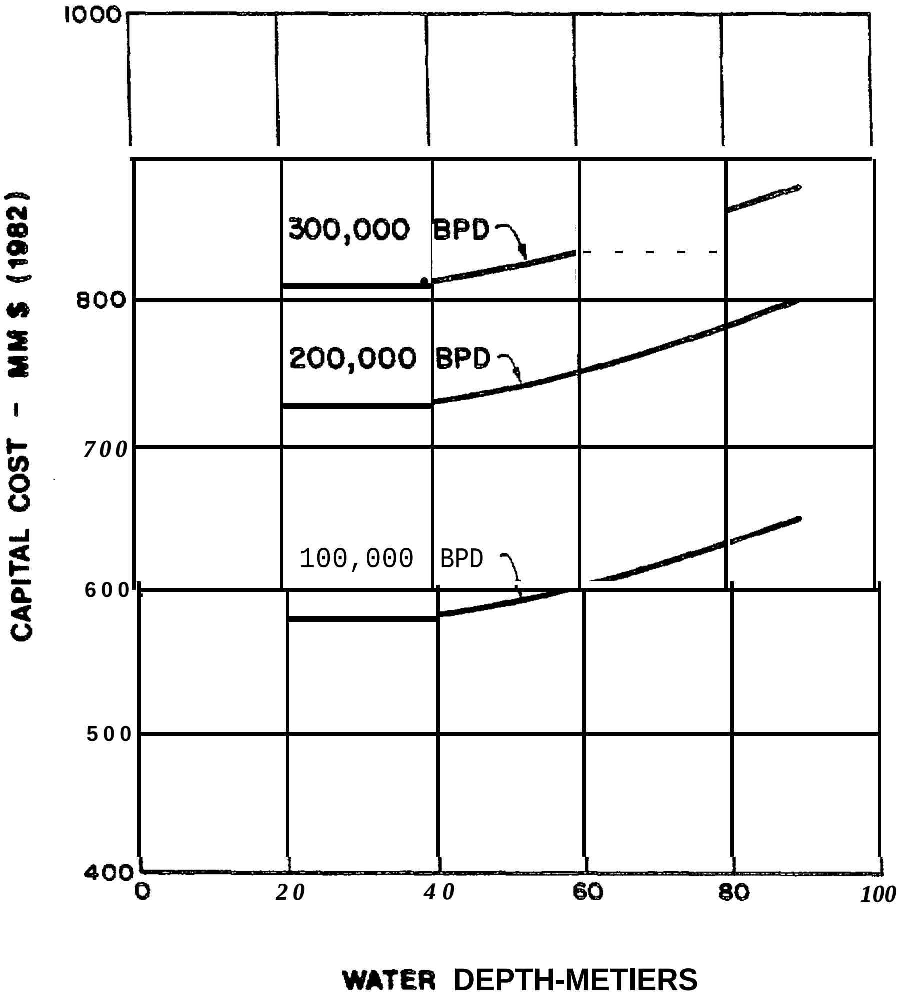
Figure 6.2-3. Generalized Conical Production Structure.



INCLUDES COST OF TOPSIDES

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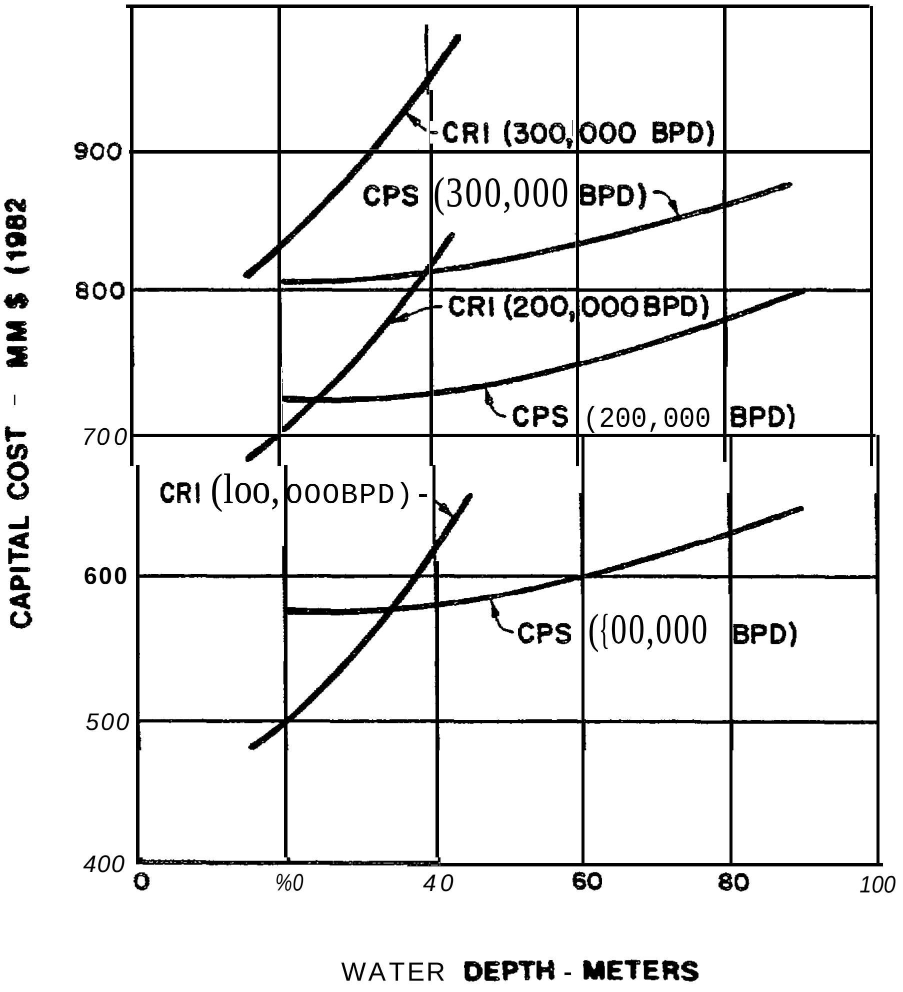
Figure 6.2-4. Generalized Conical Production Structure capital cost versus water depth.

## 6.3 PRODUCTION PLATFORM COSTS AND MANPOWER REQUIREMENTS

In Section 6.2, the costs of Caisson Retained Island production platforms and Conical Production Structures were developed. For any particular production scenario, an operator will probably use the system which results in the lowest platform cost, consistent with the selected transportation system as described in Chapter 7. Figure 6.3-1 illustrates the minimum platform capital cost versus water depthfor the three production rates considered and assuming that the source of borrow material for the CRI is located adjacent to the platform site. The figure reveals that the CPS is the most cost effective production platform concept for all water depths within the study area and for the range of production rates considered.

It must be borne in mind that the costs presented in Figure 6.3-1 are based on numerous criteria, conditions and assumptions as defined throughout this report. Significant changes in any of these factors could, of course, change the results presented.

The annual operating costs for the production platform and ancillary facilities are described in Chapter 4. In addition to these costs, a cost for maintaining the production platform structure must be considered. There is no historical basis available for determining this cost and for purposes of this study, an annual structure maintenance cost of $5,000,000 has been used for both the CRI and CPS.



**INCLUDES COST** OF TOPSIDES

CRI COST BASED ON 0 KM HAUL DISTANCE

**CRI** - Caisson Retained Island
**CPS** - **Conical Production Structure**

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Figure 6.3-1. Production platform capital cost versus water **depth.**

The manpower required for the various development drilling, production and support operations is described individually for each operation in Chapter 4.

## 7.0 TRANSPORTATION TECHNOLOGY ASSESSMENT

The primary alternative for transporting crude oil from the Diapir Field to the "Lower 48" is to install a marine pipeline to shore and a land pipeline connecting to the existing Trans-Alaska Pipeline System (TAPS). TAPS has a rated capacity of 2.0 MMBPD and is presently being utilized at only approximately 1.65 MMBPD. In addition, the capacity of TAPS can be increased, if necessary, by adding pump stations, using flow improvers and looping critical pipeline sections.

As a sensitivity case analysis, it has been assumed that TAPS will be unavailable for crude oil produced from the study area. In this case, a number of alternative transportation systems have been considered, including:

1. A marine pipeline to shore and a land pipeline to and paralleling TAPS.
2. A marine pipeline to shore and a new north-south pipeline.
3. An offshore loading/storage system and icebreaker tankers.
4. A marine pipeline to a nearshore terminal for loading icebreaker tankers.

This chapter provides an assessment of the technology, manpower requirements and costs for the major elements of the various transportation system alternatives.

For purposes of this study, transportation of the crude oil only to a warm water pipeline terminal on the southern coast of Alaska or a transshipment terminal on the Alaska Peninsula is considered. It is assumed that conventional tanker transportation cost from these terminals, including the cost of a new terminal, will be approximately the same, and therefore, the portion of the transportation cost from these terminals to the ultimate destination of the crude oil is not considered further in this study.

## 7.1 MARINE PIPELINES

For the past decade and a half, the petroleum industry has been actively engaged in the research and development of the technology for the design and construction of subsea oil pipelines in the Arctic area. Critical environmental factors affecting the design and construction of marine pipelines include ice and weather conditions, their effect on construction equipment and the effective length of construction season, the nature of the seabed soil, seabed ice gouging, and, in the permafrost zones, the prevention of permafrost degradation. Preliminary designs and cost estimates for marine pipelines have been prepared for the base case production rate of 200,000 BPD and for sensitivity case production rates of 100,000 BPD and 300,000 BPD.

Marine pipeline construction in the Beaufort Sea is technically feasible but year round pipeline repair procedures have yet to be fully developed. Marine pipeline design, installation and cost considerations are described below.

### 7.1.1 Environmental Factors

The environmental conditions in the study area and specific environmental design criteria are discussed in Chapter 3. In general, the continental shelf of the Alaskan Beaufort Sea is relatively narrow (no more than 80 km (50 mi) wide) and breaks at a water depth of 70 to 75 m (225 to 250 ft). For about nine months the ice cover of the Beaufort Sea is nearly complete, and in some years there is no ice-free period created by the retreat of the polar ice pack. Even in complete ice coverage there are always windows and polynyas present due to the effects of tides, winds and currents. Thus, "average" ice conditions have no real significance, but for preliminary evaluation purposes it has been assumed that the "average" open water season, during which pipeline construction can be carried out, is approximately 50 days.

The fast ice zone extends from shore to approximately the 20 m (65 ft) isobath. Between this and the moving pack ice is a shear zone. The ridges formed by this intense ice interaction mechanism are the elements which create deep ice gouges during grounding and subsequent movement. The grounded ridges can extend outward to approximately the 45 m (150 ft) isobath. From shore to the 15 m (50 ft) isobath ice gouging is frequent but relatively shallow. Occurrences peak in 20 to 30 m (65 to 100 ft.) of water. The deepest recorded gouge is 5.5 m (18 ft) deep in 38 m (125 ft) of water.

In near shore areas, and possibly in water depths as great as 15 m (50 ft), shallow ice-bonded permafrost could be present and must be considered in the design of the pipeline shore approach.

### 7.1.2 Design

Preliminary designs for marine pipelines for a range of production rates have been developed. For each production rate there are a number of combinations of pipe diameter, wall thickness, weight coating thickness and pump discharge pressure that would satisfy the conditions. An optimized pipeline design would require a detailed evaluation of the interrelationship of all these factors to minimize the life cycle cost of the system. For preliminary design purposes, reasonable combinations of these factors were selected based on past experience with existing pipelines and it is anticipated that the major pipeline elements are reasonably close to those. which would be obtained through a final design process.

Due to the deep water and ice cover, intermediate booster pump stations would not be cost effective for the marine pipelines and all designs have been based on providing no booster stations. The pipeline pressure drop calculations are based upon Darcy's general flow equation with friction factors taken from Stanton's Diagram utilizing F.H. Moody's relative roughness data. The pipe wall thicknesses developed meet the requirements of ANSI B31.4, "Liquid Petroleum Transportation Piping Systems," for the internal pressure developed. In most cases low temperature API-5LX-60 pipe was selected. However, in a few cases, particularly the high throughput, long pipelines, low temperature API-5LX-65 pipe was required. For marine pipelines, it is frequently found that the pipelaying stresses during construction exceed operating stresses and it is necessary to increase the wall thickness for construction purposes. For this reason, a maximum diameter to wall thickness ratio of 40 was provided. A detailed evaluation of construction techniques may indicate that slightly greater wall thicknesses are required for some of the large diameter pipelines also.

Marine pipelines would be corrosion coated and weight coated. A common method of corrosion coating is to coat the pipe with coal tar and wrap with two applications of glass wrap and a felt outer wrap with hot coal tar applied between each wrap. Corrosion coating of the pipe is extremely important to the longevity of the pipeline and a thorough investigation of optimum methods of coating for this rugged service would be required in final design. All pipelines are assumed to be catholically protected.

The concrete weight coat would be reinforced with wire mesh. Concrete of densities ranging from 2.15 to 3.2 tonnes per $m^3$ (135 to 200 lb per $ft^3$) are available. The weight coated pipe selected for the preliminary pipeline design has a minimum negative buoyancy of 1.25 with the pipeline empty. A final design would require an evaluation of currents and wave action expected during the installation to determine the optimum negative buoyancy.

The concrete weight coat required is as follows:

| PIPE DIAMETER<br>in. | WEIGHT COAT THICKNESS<br>cm (in.) |
|---|---|
| <14 | 4.0 (1.5) |
| 14-24 | 5.0 (2.0) |
| 26-30 | 6.5 (2.5) |
| 32-34 | 7.5 (3.0) |
| 36-40 | 9.0 (3.5) |

For the preliminary pipeline designs, it was assumed that the crude oil would enter the pipeline at 60°C (140°F). For an uninsulated 24 inch diameter marine pipeline, operating at 200,000 BPD in a seawater environment at 0°C (32°F), the temperature of the crude falls to 5°C (41°F) after 20 km (12 mi) and to 0°C (32°F) after 80 km (50 mi). For preliminary design purposes, in cases where the pipelines are shorter than 80 km (50 mi), the average temperature of the crude oil in the lines was taken into account. However, for longer pipelines, the viscosity at 0°C (32°F) was used for the whole line.

Pipeline insulation may be required if crude oil properties are not as suitable for pumping as those assumed or if extensive permafrost is encountered. Buried, insulated marine pipelines are technically feasible but pipeline costs would be significantly increased.

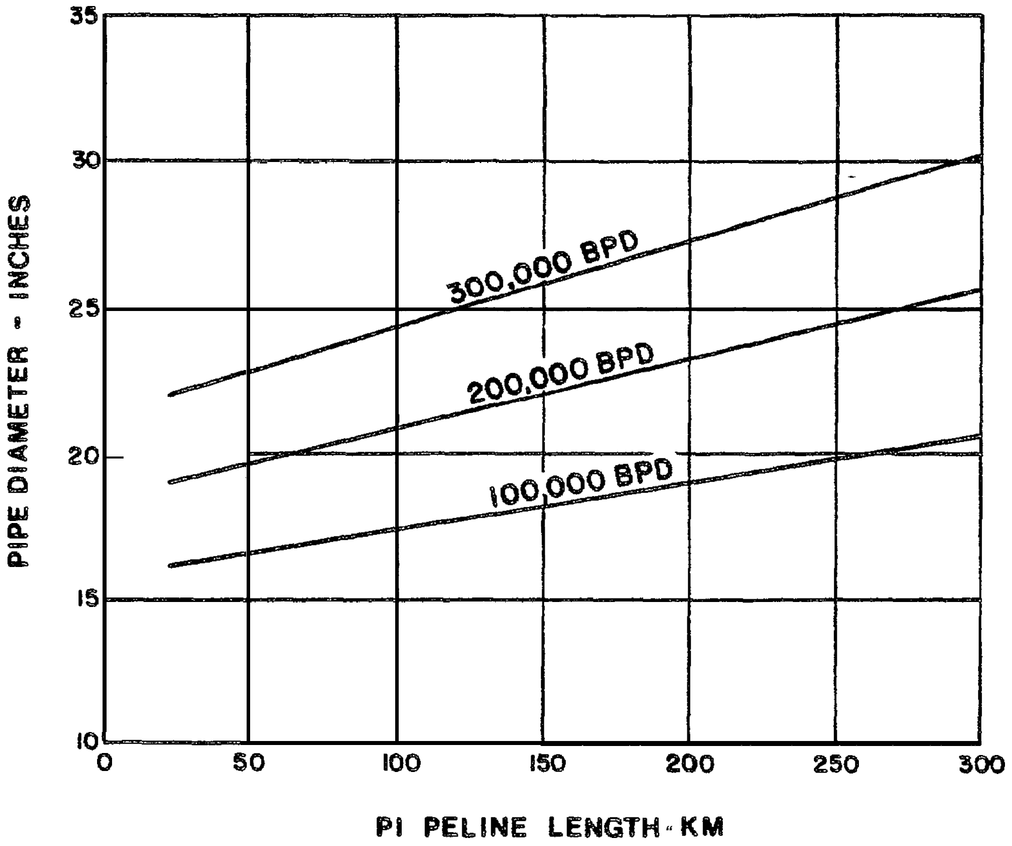

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Figure 7.1-1. Marine pipeline pipe diameter versus pipeline length for various production rates.

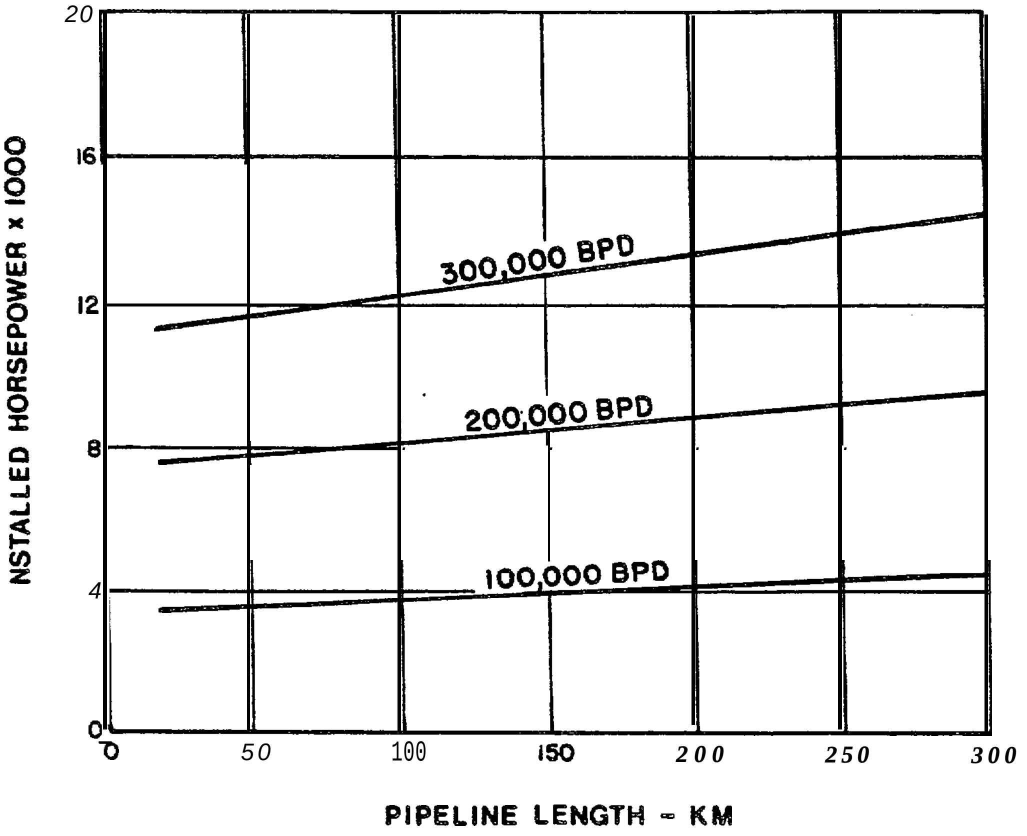

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Figure 7.1-2. Marine pipeline installed horsepower versus pipeline length for various production rates.

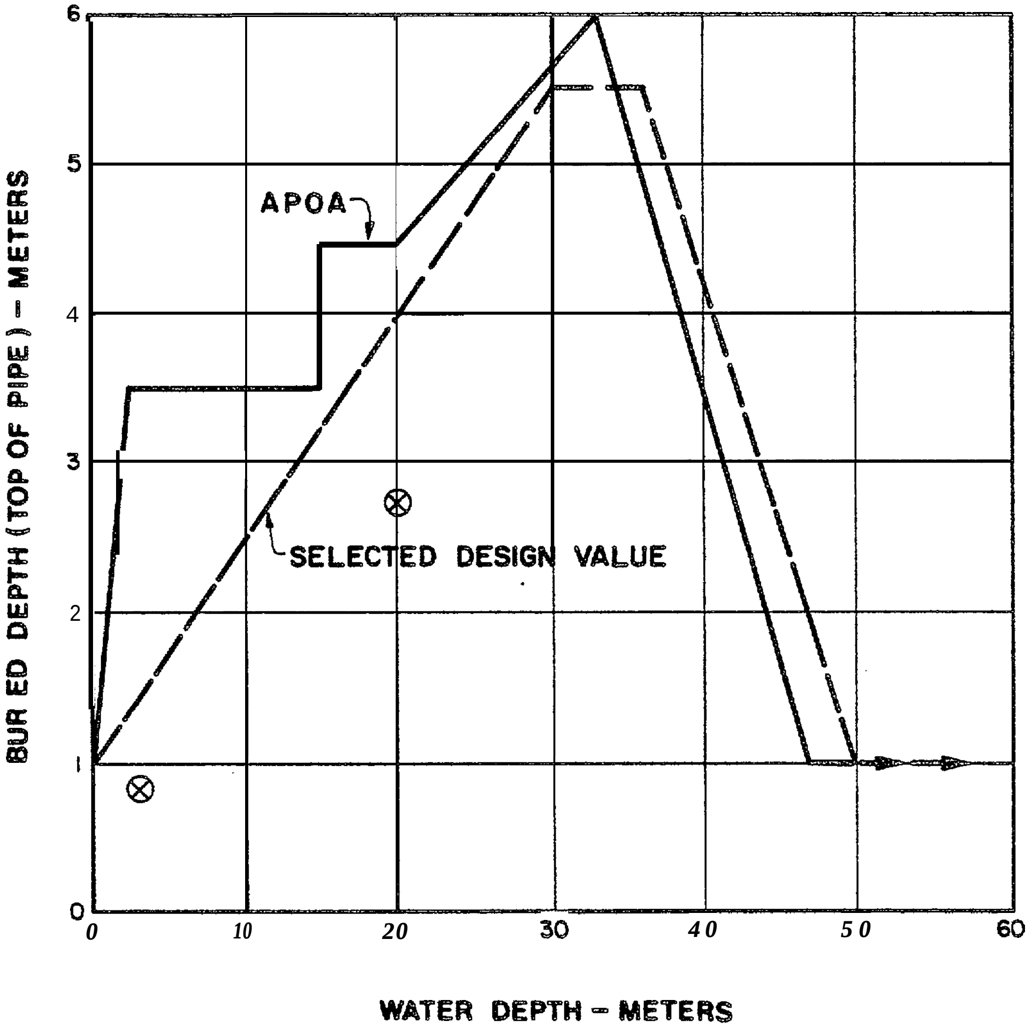
The pumping equipment selection philosophy utilized for this study is to install two 50 percent capacity pumps, with gas combustion turbine drivers, plus a third 50 percent capacity pump and driver as a spare. Flash gas from the gas-oil separators would be used to fuel the gas combustion turbines.

Figures 7.1-1 and 7.1-2 present the results of the preliminary design of the marine pipelines. Figure 7.1-1 illustrates the required pipe diameter as a function of pipeline length for the three production rates considered. Figure 7.1-2 illustrates the required installed horsepower (including the 50 percent capacity spare) as a function of pipeline length for the same three production rates. These figures are valid only for crude oil with the properties listed in Section 3.3.1 and are very sensitive to the actual crude oil properties. Figures 7.1-1 and 7.1-2 are only approximate because the pipe diameter and installed pumping horsepower are interdependent for a given pipeline length and production rate. For example, by providing a larger pipe diameter than indicated in Figure 7.1-1, for a given pipeline length and production rate, the installed horsepower required would be less than that indicated in Figure 7.1-2. However, for preliminary evaluation of a particular scenario, Figures 7.1-1 and 7.1-2 will provide reasonable estimates of pipe diameter and installed horsepower.

### 7.1.3 Trenching Requirements

The primary reason for pipeline trenching in the Arctic is to lower the pipe below ice gouge hazards. Since few very deep ice gouges have been found, deep trenching is very expensive and the majority of gouges are relatively shallow, trenching depths must be decided on the basis of acceptable risk. This requires gathering and evaluating data on the frequency, depth and location of gouges, and determining the recurrence interval for various gouge depths along the proposed pipeline route. Several proprietary studies have been or are being carried out in this regard. An acceptable recurrence interval must then be established, say 100 years, and the trench depth determined accordingly. The depth of the trench must be based not only on the ice gouge depth but also on consideration of the force exerted on a pipeline buried below a gouge. Consideration should be given to the provision of automatic block valves at intervals along the pipeline to minimize the quantity of oil that would be spilled should an event more severe than the design event cause a pipeline rupture.

For trenching cost estimating purposes, preliminary trench depth requirements are presented in Figure 7.1-3. The solid line indicates Canadian Beaufort Sea burial depth information from APOA (Winter 1983/84), with additional recommendations calculated based on Weeks et al. (1980) for the Alaskan Beaufort Sea. The burial depths used for the preliminary designs and cost estimates of this study are indicated by the dashed line in the figure.



⊗ **Based on** Weeks et. al. (1980)

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**Figure 7.1-3.** Marine pipeline **trench depth** requirements versus water depth.

A number of trenching methods are available for consideration for Arctic applications. Section 4.1.2 contains a discussion of the cutter suction dredge, which is the most efficient dredge for deep-trenching in a variety of soils. However, existing cutter suction dredges are limited to dredging depths of 30 m (100 ft) and have forward speeds which are too slow for the short construction season. Therefore, new, specially designed dredging equipment is required. Based on the burial depths shown in Figure 7.1-3 and the unit costs for dredging a pipeline trench with a cutter suction dredge as given in Figure 4.1-6, the cost of trenching on a per kilometer basis as a function of water depth has been calculated and is presented in Figure 7.1-4. These costs are based on medium dense material and trench side slopes of 2.5:1.

An alternative method of trenching is to use a mechanically simple subsea plow arrangement. If a properly designed plow is utilized, it may be possible to plow 3 m (10 ft) deep trenches in a single pass at a plow speed of about 3.5 km per hr (2 knots), provided a high horsepower (16,000 shaft hp or greater) tow vessel is used. This speed is equivalent to 45 km (27 mi) per day, but in practice there are mobilization/demobilization times and plow inspection and repair times which will reduce the trenching rate. Trench depth may be enhanced by using multiple passes (NPC, 1981).

A number of mechanical cutting devices are now in various stages of product development, but it appears that, at this point, the most

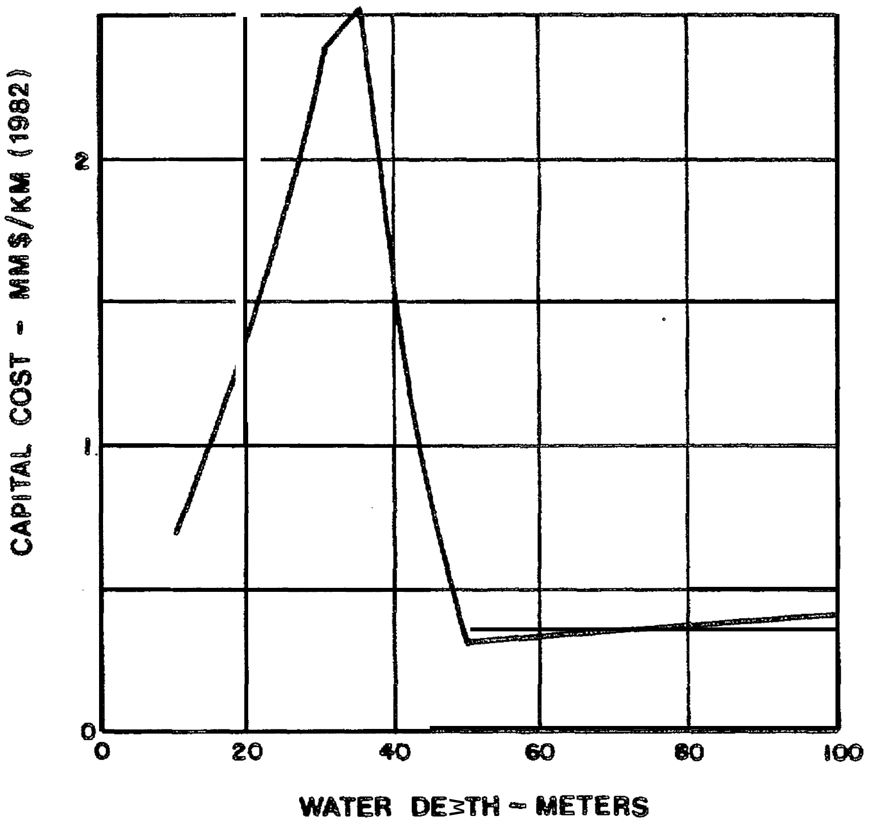

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Figure 7.1-4. Marine pipeline trenching cost versus water depth.

promising application for these slower, stiff-soil-cutting machines is to do additional post-trenching in localized areas where the plow encounters difficulty in achieving the desired trench depth. One other system of trenching in sands and silts is to use hydraulic pressure to create a fluidized soil bed around the pipeline, whereby the pipeline is lowered by gravity to the desired depth. The utility of this method for deep trenching in the Arctic has yet to be proven. The method most widely used to date is the jet sled method whereby water jetting is used to liquefy the soil around the pipeline, causing it to lower by gravity. This shallow-trench method is not likely to-be useful for fast, deep trenching in the Arctic (NPC, 1981).

### 7.1.4 Installation Methods

There are no existing major marine pipelines in the Beaufort Sea, however, there is no doubt that their construction is technically feasible. In the Western study region, pipelines as long as 300 km (180 mi) may be required while in the Central and Eastern regions, pipelines will probably not exceed 100 km (60 mi). It is anticipated that pipelines longer than approximately 15 km (10 mi) would be installed by a large semi-submersible or ship-shaped lay barge with icebreaker support. The lay barge would require ice-strengthening, modified mooring system for operations in ice, enclosed work areas and a heat recovery system. These vessels can lay pipe at a rate of approximately 2 km (1.5 mi) per day and can operate in significant wave heights of 4.5 to 5.5 m (15 to 18 ft). Therefore, in the Central and Eastern regions the lay barge can complete the installation in one "average" season. Long pipelines in the Western region will require two "average" seasons for installation. It should be pointed out that there is a large variability in the open water or light ice summer construction season and there is a significant probability that the construction season will be short or non-existent in any given year.

Short pipelines and the shallow water portion of long pipelines will probably be installed by the bottom pull method. With this method, long pipe strings are fabricated on shore and then pulled into position in the trench. Installation methods using the ice as a working surface may also be used.

An alternative installation method is the bottom-tow. With this method, pipe strings are fabricated on shore and then pulled into position in the trench in 8 to 15 km (5 to 10 mi) strings. The strings are joined to form the completed pipeline. This method requires a sizable pipe assembly site to be constructed on shore and due to the rapid increase in pulling force with distance will probably be limited to the construction of relatively short pipelines.

It is most likely that in water depths less than 50 m (165 ft) the trench in which the pipeline will be installed, will be dredged the season before the pipeline is to be laid. Therefore, the trench dimensions and sideslopes must be such that it will remain open for at least one year. Backfill of the trench in deeper water will probably not be required.

### 7.1.5 Shore Approach

Shore approaches impose special problems in the Beaufort Sea. Where bonded permafrost exists in the shore approach zone special measures must be taken to protect the permafrost. Such measures include trenching and insulating the pipe and/or refrigerating the trench, tunneling or directional drilling (Marcellus and Palmer, 1979), making a gravel berm in which to lay the pipeline or constructing an elevated joint-and-pile bridge. For short shore approaches of less than 2 km (1.2 mi) with bonded permafrost present, a gravel berm method would probably be cost effective but permitting agencies have expressed a reluctance to allow this type of shore approach. The Corps of Engineers has stated that a buried insulated pipeline is the preferred shore approach and permits for future gravel berm shore approaches must demonstrate that a buried pipeline approach is not feasible, For longer shore approaches a massive joist and pile structure might be required. Of course, each specific location must be carefully evaluated using more site-specific data, presently not available.

There has been considerable recent concern regarding the effect of long causeways on the migration of marine fauna. At this time it appears that the State of Alaska will require that any long causeways be breached by periodic gaps up to 60 m (200 ft) long. While such a requirement may have a significant effect on the cost of the shore approach, it would have a small effect on the total marine pipeline cost for projects within the study area.

### 7.1.6 Manpower

Marine pipeline manpower requirements are included with the production platform topsides manpower.

### 7.1.7 costs

There are no Beaufort Sea marine pipeline cost data available on which to base construction cost estimates. Therefore, cost estimates have been developed in the following manner:

- Materials:
  - Pipe @ $1500 per tonne
  - Corrosion Coating @ $15 per $m^2$
  - Weight Coating @ $500 per $m^3$
  - Cathodic Protection @ $7 per kg
- pumps: $3,500 per installed hp
- Transportation: $650 per tonne
- Modification for Arctic Operations: $20,000,000

- Mobilization/Demobilization:
  - Pipeline length less than 100 km @ $13,000,000
  - Pipeline length greater than 100 km @ $26,000,000
- Shore Crossing and Structure Connection: $20,000,000
- Installation: $400,000 per km using a large semi-submersible lay barge
- Trenching: as per Figure 7.1-4.
- Engineering and Management: 10 percent of total cost

Figure 7.1-5 shows pipeline construction costs versus pipeline length for various pipe diameters developed on the above basis. As indicated above, the installed cost of the pipeline includes pumping equipment, (pumps, drivers, piping, valves and controls). The installed cost of the pumping equipment has been assumed to be $2,500 per installed horsepower. In addition, an allowance of $1,000 per installed horsepower has been added to cover the cost of the space that the pumping equipment will occupy on the production platform. The actual cost of such space cannot be determined within the scope of this study and the selection of $1,000 per horsepower is, consequently, quite arbitrary.

Operating costs of marine pipelines are very difficult to establish. Typically, operating costs are considered to range between 1 and 5 percent of capital cost depending on the extent of inspection and repairs required (Han-Padron, 1984). For purposes of this study, it has been assumed that average annual operating costs will be approximately 3.5 percent of the capital cost. Operational costs versus pipeline length for various pipe diameters are presented in Figure 7.1-6.

### 7.1.8 Sensitivity

The feasibility and cost of long marine pipelines can be extremely sensitive to the properties of the crude oil they must transport. The preliminary designs have been based on the base case crude oil properties listed in Section 3.3. These properties are for a light crude oil with excellent pumping qualities. For heavier crude oils, pipeline. insulation may be required and pipeline diameters/pumping horsepowers would be increased with corresponding increases in costs. A crude oil with a pour point above the seawater temperature would require special provisions, such as heating of the pipeline, if it is to be pumped long distances. Such provisions would significantly increase the capital and operating costs shown in Figures 7.1-5 and 7.1-6.

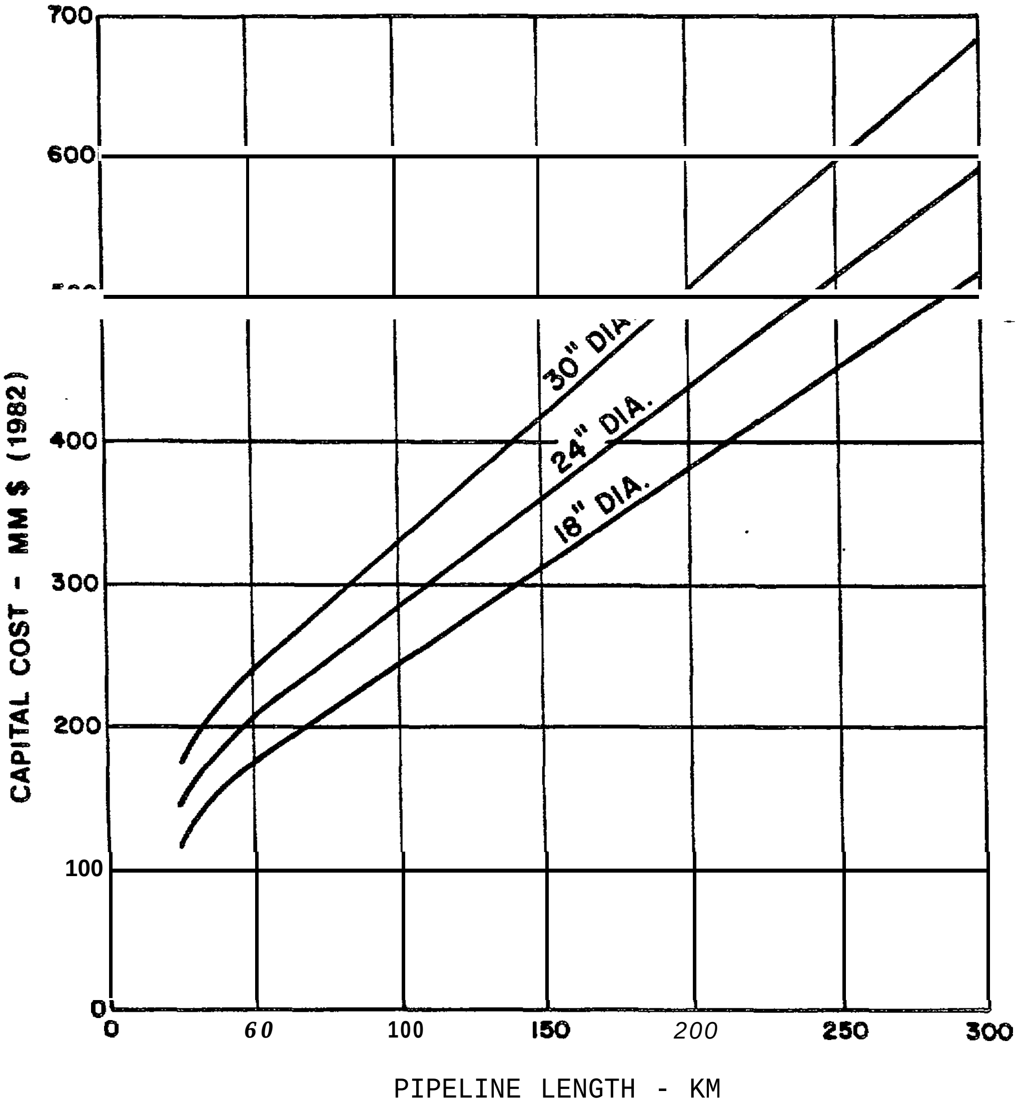

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Figure **7.1-5.** Marine pipeline capital cost versus pipeline length.

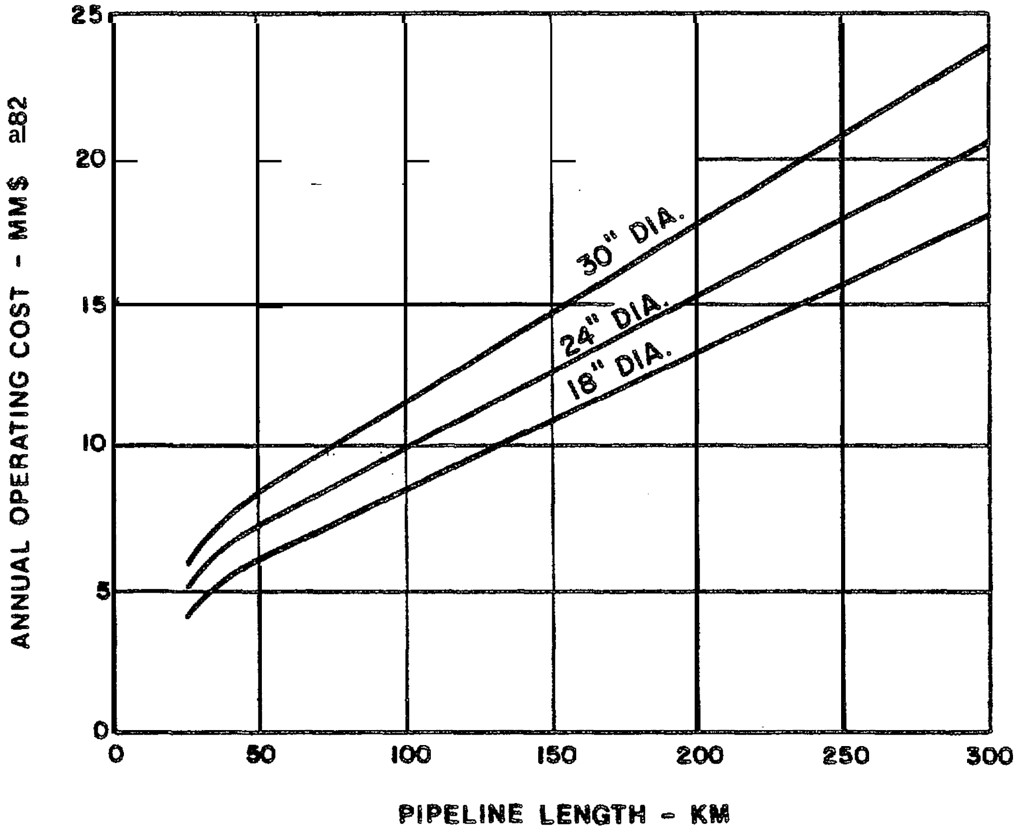

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Figure 7.1-6. Marine pipeline annual cost versus pipeline length.

## 7.2 LAND PIPELINES

### 7.2.1 Technology

The Trans-Alaska Pipeline System was placed into operation in August 1977. Since that time several other onshore petroleum pipelines in the Alaskan and Canadian Arctic have been constructed. Therefore, considerable technical and cost data are available. The National Petroleum Council (1981) report has an extensive treatment of land pipelines and land pipeline sizes and booster pump station requirements, have been developed from that report. For a new land pipeline, the assumed pipe diameters versus production rate are shown in Figure 7.2-1.

### 7.2.2 Manpower

Based on the TAPS experience, a crew of approximately 25 people is required to operate a pump station on an Arctic land pipeline. The number of pump stations required on a particular line depends on a number of factors, but, based on the NPC (1981) study, one pump station is required for approximately each 150 km (100 mi) of pipeline and manpower estimates may be based on this factor.

### 7.2.3 costs

Land pipeline costs presented in the NPC (1981) study are based

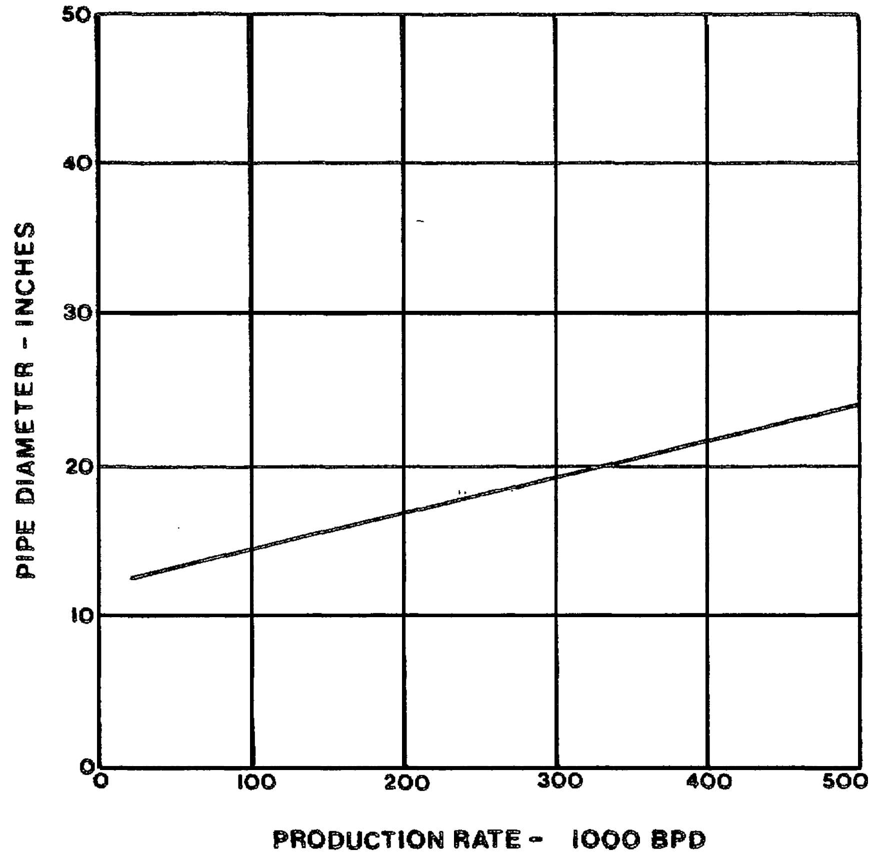

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Figure 7.2-1. Land pipeline pipe diameter versus production rate.

primarily on the TAPS experience. The cost of a recently constructed Canadian Arctic pipeline is almost an order of magnitude lower than the land pipeline costs indicated in the NPC (1981) study. The cost of the ARCO Kuparuk pipeline completed in 1981, although significantly higher than the cost of the Canadian Arctic pipeline, is reported to be less than 25 percent of that given in the NPC (1981) report. The difference in costs between the Kuparuk and Canadian pipelines is probably attributable to the difference in Alaskan and Canadian regulations. Arctic land pipeline costs are extremely sensitive to regulatory requirements and the economic state of the pipeline construction industry at the time the construction contract is awarded. Considering the fact that the Canadian and Kuparuk pipelines were constructed during a time when the pipeline construction industry was extremely depressed, the NPC (1981) costs appear to be too high by at least a factor of three. Therefore, for this study, land pipeline costs have been assumed to be one third of the costs indicated in the NPC (1981) study. Land pipeline capital costs have been divided into four categories:

- above ground with haul road,
- below ground with haul road,

and for a pipeline that parallels TAPS:

- above ground without haul road,
- below ground without haul road.

The capital costs per kilometer for each category versus pipe diameter are shown in Figure 7.2-2. Land pipeline annual operating costs have to be taken as 2 percent of the capital cost as indicated in Figure 7.2-2.

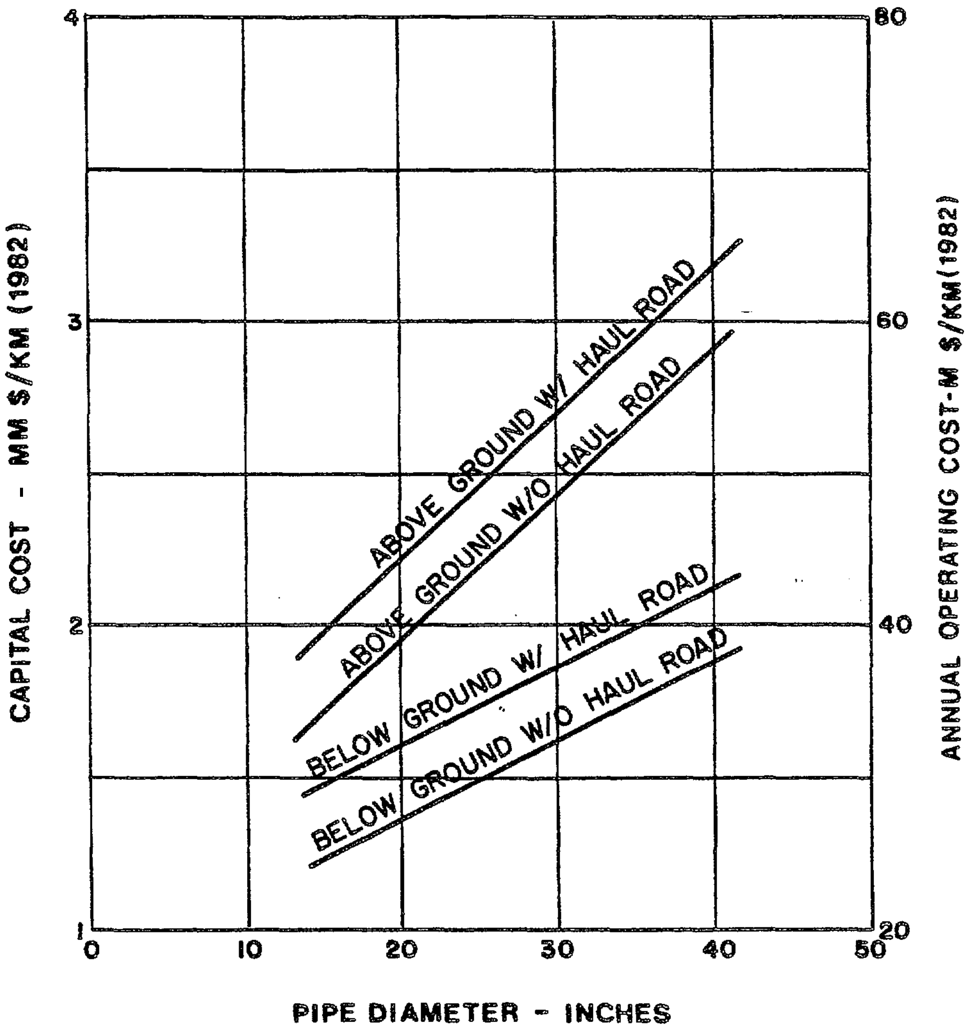

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Figure 7.2-2. Land pipeline capital and annual costs versus pipe diameter.

## 7.3 OFFSHORE LOADING TERMINALS

A marine terminal, as used throughout this report, includes tanker loading/unloading facilities, crude oil storage, marine pipelines connecting the storage facilities to the tanker loading/unloading facilities, pumping/metering/piping facilities, living quarters for operating crew, power plant, communication facilities and all ancillary facilities required for a complete tanker loading/unloading terminal. In general, three types of terminals are considered, offshore terminals, nearshore terminals and transshipment terminals.

An offshore terminal is defined as a terminal where all facilities, including crude oil storage and tanker loading facilities, are located near or within the production platform. A nearshore terminal is defined as a receiving terminal for a marine pipeline from the production platform, with onshore storage tanks and a tanker loading facility located as close to the storage tanks as water depths permit. A transshipment terminal is defined as a terminal located in ice-free waters, with facilities for unloading icebreaker tankers, storing the crude oil in onshore storage tanks and loading conventional tankers. Offshore terminals are discussed in this section. Nearshore terminals are discussed in Section 7.4. Transshipment terminals are outside the scope of this study, and the reader is referred to Han-Padron Associates, 1984.

### 7.3.1 Selection Criteria

The selection of the optimum offshore loading terminal for a particular scenario depends on many factors. In order to evaluate the various alternatives which maybe feasible for the study area, the following criteria were used:

- All tankers and mooring facilities will be equipped with the most modern navigation systems and mooring operations will take place during periods of reduced visibility (fog) and at night.
- All tankers will be equipped with a bow manifold and a bow control house for mooring operations.
- Ice conditions will not prevent mooring and loading operations. Icebreaker assistance may be required to achieve this.
- Mooring operations will take place in seas with a significant wave height up to 3.0 m (10 ft) and loading operations will continue in seas with a significant wave height up to 4.5 m (15 ft).
- Unscheduled maintenance will cause 5 percent maintenance downtime. (Scheduled maintenance is assumed not to interfere with tanker operations.)
- The throughput will range between 100,000 BPD and 300,000 BPD.
- The terminal will be served by Class 8 icebreaker tankers of 250,000 DWT or less.

- Two Class 8 icebreakers will be available to clear the mooring facilities and approaches.
- Moored tankers must be free to "weathervane" in order to minimize the forces acting on the system.
- The mooring structure must have sufficient width at the waterline to provide a lead in moving ice wider than the beam of the tankers in order to reduce mooring hawser loads to a manageable level.
- All mooring system and loading system elements must remain clear of the ice at all times.
- The pumping/metering/piping system will be sized to load all tankers in 12 hours.
- Since all tankers must have segregated ballast, no ballast water treatment facilities are required.

The optimum number of tanker berths to be provided at a terminal depends on:

- the size of ships using the terminal,
- the required berth occupancy time per ship,
- queuing delays as a function of the number of berths,
- frequency and duration of berth closures due to weather conditions,
- the cost of ship waiting time,
- the capital cost for new berths, and
- the annual operating cost for new berths.

A detailed evaluation of the optimum number of berths at the terminal is not warranted at this preliminary evaluation stage. Based on operating experience at existing terminals, a berth occupancy rate of 40 percent is considered the maximum economical rate for a single berth terminal in the deeper waters of the Beaufort Sea. This results in the requirement for only one berth for all throughput rates considered. It has been proposed on a number of occasions that more than one berth be provided in order to have a redundant system to insure availability of at least one berth at all times. However, this is considered to be an uneconomical solution and this study is based on the assumption that a single berth can be installed with a sufficiently high reliability to eliminate the need for a redundant berth.

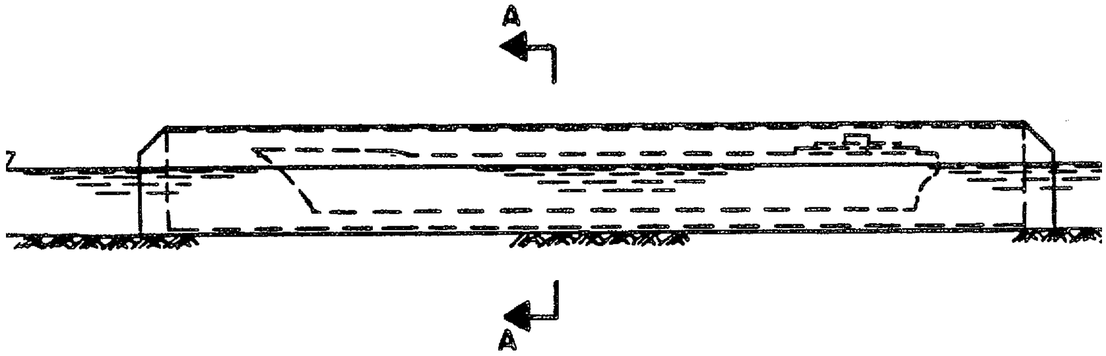
The determination of the optimum crude oil storage capacity for any particular scenario requires a thorough evaluation of the incremental cost of storage capacity, the cost of tanker delay time, the incremental cost of increased tanker size, the frequency of tanker arrivals, the effect (cost) of reduced production rate or production shut-in, and a number of other factors. A detailed evaluation of the optimum storage capacity is not warranted for this study. Rather, it has been assumed that the optimum storage capacity is the equivalent of approximately ten days throughput.

### 7.3.2 Proposed Concepts

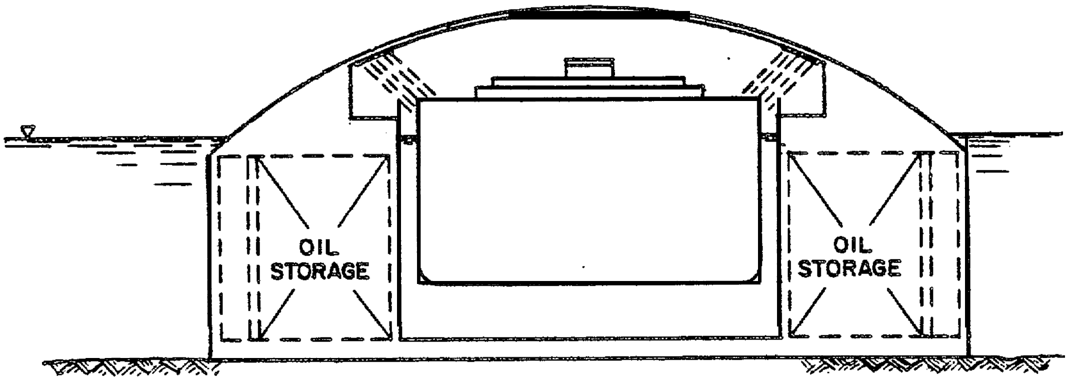
The concept of transporting petroleum products by icebreaker tanker from the Beaufort Sea has been under serious consideration for more than fifteen years. There are no existing offshore loading terminals that would be suitable for the study area, but a number of different concepts have been considered over the years, both with and without internal storage capacity. Some early concepts include the Controlled Environment system shown in Figure 7.3-1, the Island system shown in Figure 7.3-2 and the Underwater SPM system shown in Figure 7.3-3 (VHA, 1969). Concepts recently given serious consideration include several variations of the vertical cylindrical mono-tower and the truncated conical tower shown in Figures 7.3-4 and 7.3--5, respectively, the Arctic Production and Loading Atoll (APLA) discussed in Section 6.1, and others.

The mono-tower has been proposed for use in relatively shallow water and would not be suitable for the deeper waters of the study area. The truncated conical tower is more suited to deeper water. But the cost of both systems increases rapidly with increasing depth. The questions of rubble buildup around the tanker mooring structure in water depths less than approximately 30 m (100 ft), and the effectiveness of icebreakers in clearing rubble, have yet to be resolved. In relatively shallow water depths, ice rubble buildup around the production platform structure or island would require the location of the loading terminal to be at least 5 km (3 mi) away from the production platform.

The APLA concept has been proposed for use in the Canadian



ELEVATION



SECTION A-A

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Adapted from : VHA , 1969

Figure 7.3-1. Controlled Environment offshore loading system.

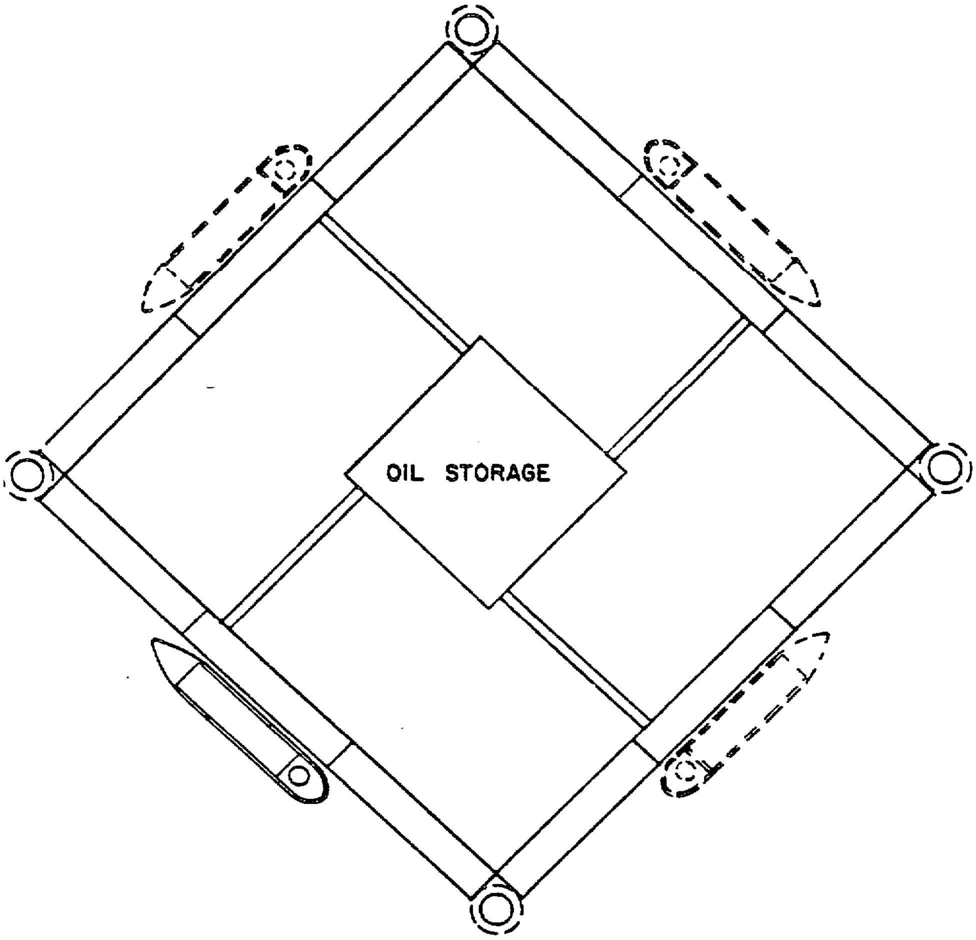

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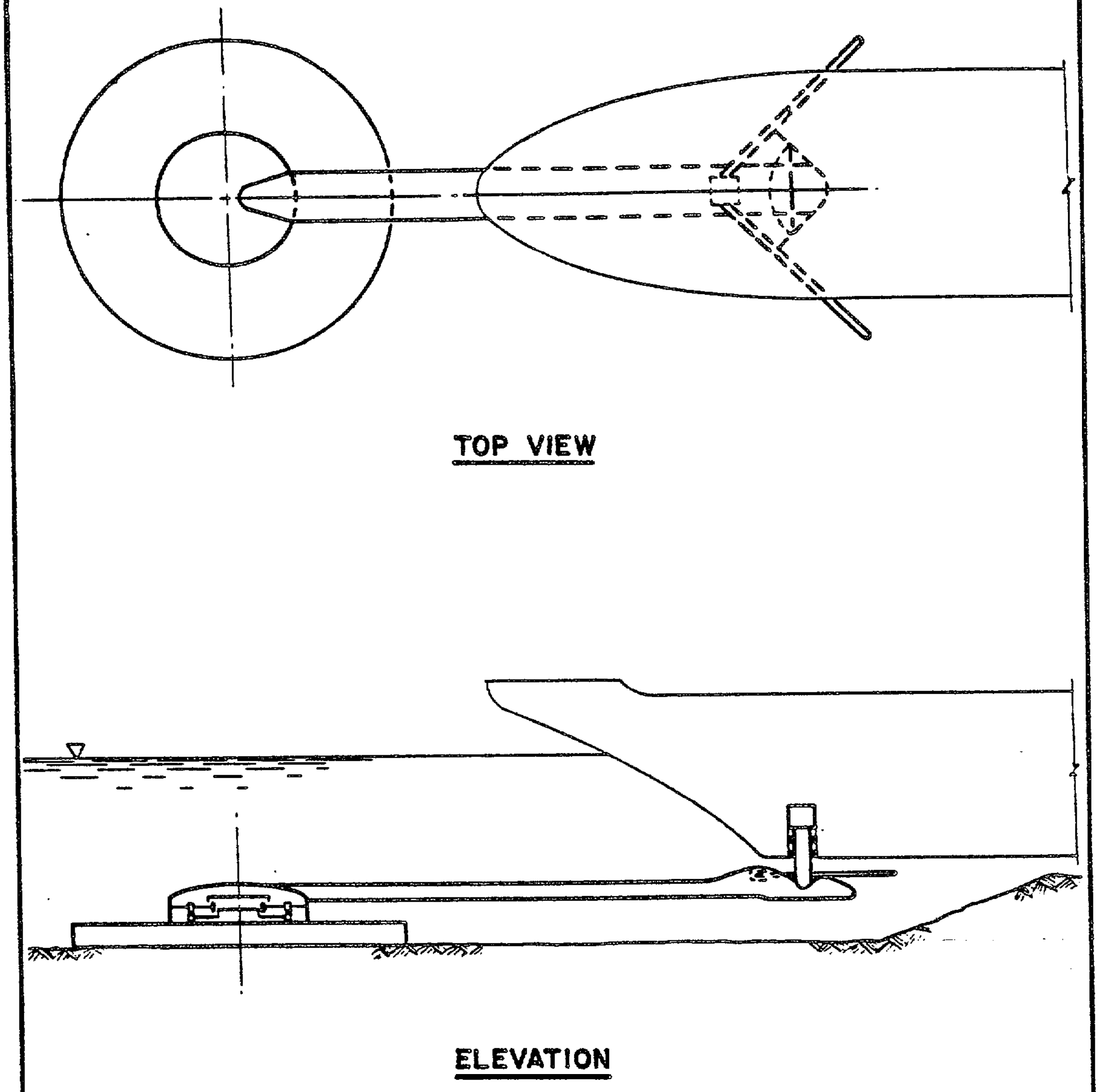
Figure 7.3-2. Island offshore loading system.



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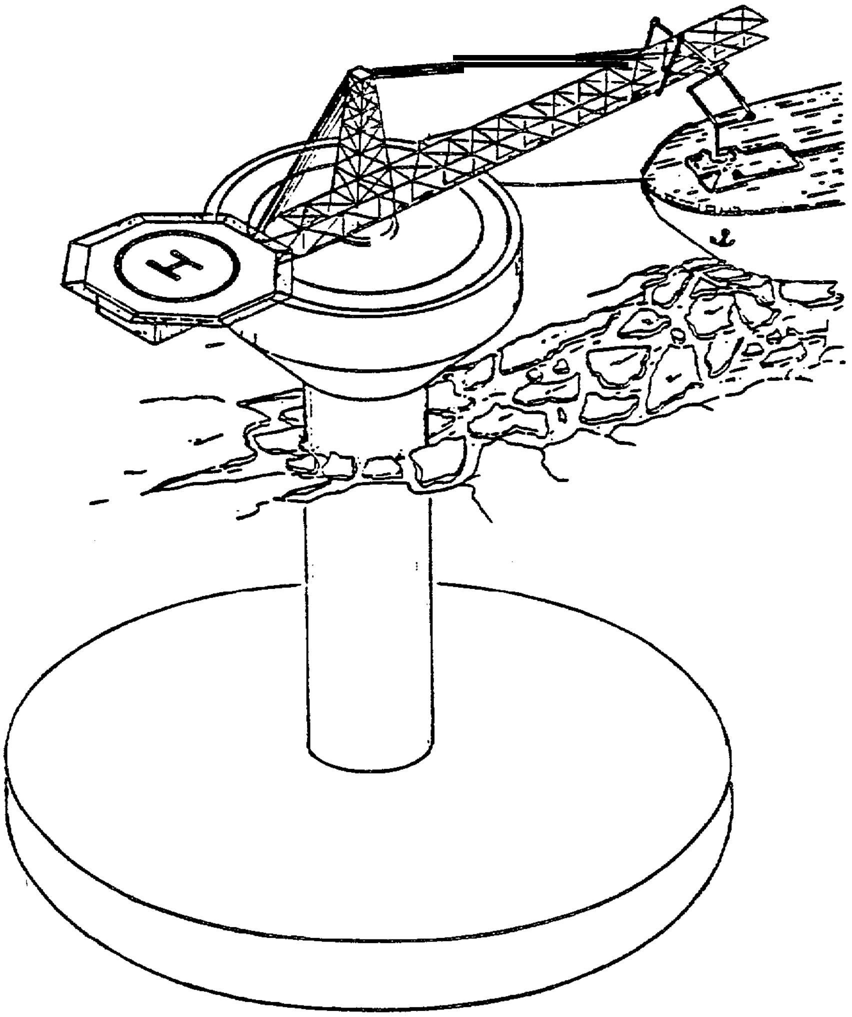
Adapted from: VHA, 1969

Figure 7.3-3. Underwater SPM offshore loading system.



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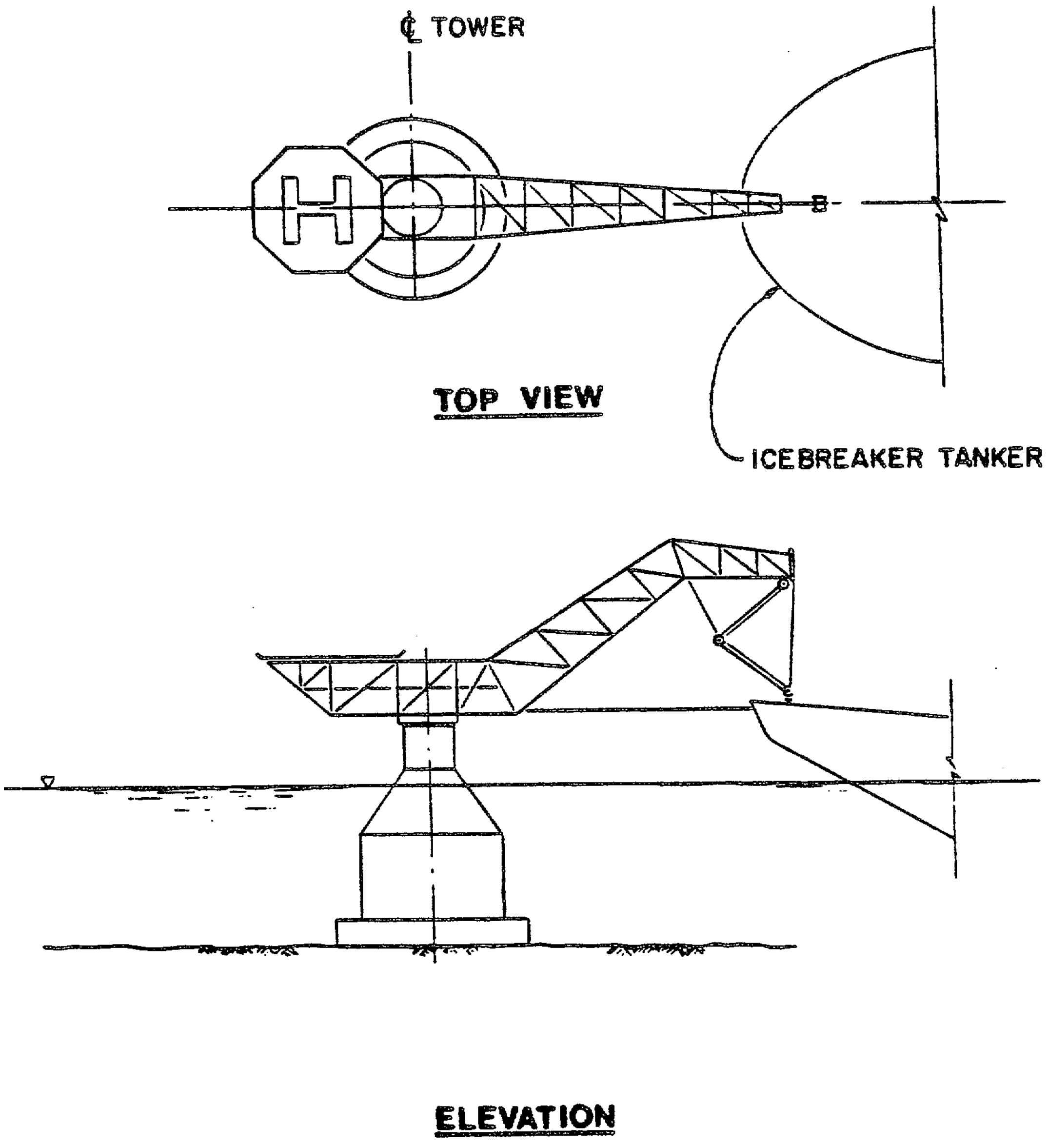
Adapted from: Bechtel, 1979

Figure 7.3-4. Monotower offshore loading system.



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Adapted from: Han-Padron, 1984

Figure 7.3.5. Truncated conical tower offshore loading system.

Beaufort in water depths between 60 and 75 m (200 and 250 ft). However, the wide range of water depths considered, the questionable availability of the large quantities of dredged material required and the question of maintaining the lagoon and entrances sufficiently ice free to permit tanker operations at all times, have eliminated this concept from further consideration in this study.

Offshore, deepwater terminal concepts for loading submarine tankers have been proposed but submarine tankers are not presently considered suitable for the study area and consequently submarine loading terminals are not considered further.

Several underwater crude oil storage structure concepts have been developed but their cost is significantly greater than the incremental cost of providing crude oil storage capacity within the production platform and consequently these concepts are not considered further.

### 7.3.3 Selected Study-Basis Concept

As mentioned above, a number of offshore loading terminal concepts have been proposed. However, for purposes of this study, none are considered cost effective. Based on the criteria listed in Section 7.3.1 and the fact that the optimum production platform for the study area is considered to be a large, prefabricated, bottom founded structure, as discussed in Section 6.2, it has been assumed that the use of the production platform as the offshore loading terminal is the most cost effective alternative.

For alternatives that utilize a tanker transportation system, the production platform will be modified to increase the width at the waterline and to provide adequate crude oil storage capacity. A seawater displacement system will be utilized to balance Internal and external pressures and to maintain sufficient structure negative buoyancy when the crude oil is withdrawn from storage. When crude oil is being pumped into the storage chambers, the internal seawater will be displaced to a ballast water treatment facility located in the upper section of the structure. The treated water will be discharged into the sea.

The use of the production platform as the offshore loading terminal provides the following obvious benefits over the use of an independent structure:

- significantly lower capital cost,
- lower operating cost,
- lower manpower requirements, and
- consolidation of operations at a single location.

However, the concept does have several areas of concern requiring further study, particularly:

- difficulty of arranging a loading system that will permit the moored tanker to weathervane,
- ability to provide sufficient fendering to prevent a

catastrophic collision between an approaching tanker and the production platform,

- capacity and behavior of mooring hawsers, and
- ability to adequately clear ice rubble at shallow water locations.

Several possibilities exist for providing a tanker loading system that will permit the tanker to weathervane. However, they have not been developed (within the public domain) beyond the conceptual stage. For purposes of this study, the tanker loading system has been assumed to consist of numerous loading stations located around the periphery of a circular topside structure. Each loading station is capable of oscillating about its at-rest position a distance approximately equal to one half the distance between the loading stations. The tanker mooring system is capable of 360° rotation around the topside structure. Thus , small changes in direction of the moored tanker can be tolerated by each loading station. A major change in ice flow direction and/or wind direction, however, will require cessation of loading operations, disconnection from the loading station, and reconnection at another loading station.

The icebreaker tanker must approach the production platform virtually head-on in order to moor. It will come to a stop at a predetermined distance from the structure and the icebreaker support vessels will be used to pass a hauling line between the tanker and structure for final positioning and mooring.

The tanker and the structure will be equipped with the best available navigation equipment to permit safe navigation during periods of poor visibility. During periods of heavy ice cover, with the ice moving, a lead, or shadow, of broken ice will be created by the structure which will assist in guiding the tanker during the mooring approach. The most difficult mooring approach will probably be during periods when there is a heavy stationary ice pressure field in the vicinity of the platform. In this case, the icebreakers will be required to create a path for the tanker to use in making its approach.

The structure will be equipped with a very substantial fender system to minimize potential damage in the event of an improper mooring approach. The fender system will probably be suspended from the deck structure and be retractable to clear large ice features. As for the loading system, such a fender system is only in the conceptual design stage.

The development of a system to moor the tankers to the tower during periods of ice cover will require special attention. Further study is required to determine the magnitude of the mooring hawser force that can be developed, particularly when the tanker is moored in an ice field that changes direction of flow. However, the mooring force is expected to be at least an order of magnitude higher than maximum mooring hawser forces at existing offshore loading systems. Therefore, conventional nylon or polypropylene hawsers will probably not be suitable and ultra-high-strength hawser materials, such as kevlar or steel wire, will be required. The elastic behavior and durability of these materials in the extreme low temperatures of the Beaufort Sea environment must be evaluated.

The extent of ice rubble buildup that can be expected around the platform is still unknown. It is anticipated that rubble buildup will not occur in water depths greater than approximately 30 m (100 ft). In shallower water, some buildup may occur and it has been assumed that the icebreakers will be able to manage the ice sufficiently to prevent the buildup from interfering" with tanker mooring and loading operations. Further study of this problem is required.

### 7.3.4 Manpower and Costs

Since the offshore loading terminal and the production platform are combined in the same structure, the additional manpower required will only be approximately 10 men, times a rotation factor of two.

The increase in capital cost to permit the production platform to function as an offshore loading terminal is approximately $100 million for all study area water depths. This increase in cost results primarily from the following factors:

- provision of a loading system,
- provision of a mooring system,
- provision of a fender system,
- increase in waterline diameter of the structure, which increases the horizontal component of the design ice force from 470 MN (106,000,000 lb) to 730 MN (164,000,000 lb).
- increase in submerged volume of the structure to provide 300,000 $m^3$ (2 million bbl) storage capacity, and
- provision of a ballast water treatment system.

The increase in annual operating cost is approximately $5 million resulting from the increased size of the crew and maintenance of the additional systems required for tanker mooring and loading and crude oil storage.

## 7.4 NEARSHORE LOADING TERMINALS

As mentioned previously, a nearshore terminal is defined as a receiving terminal for a marine pipeline from the production platform, with onshore storage and a tanker loading facility located as close to the storage facilities as water depths permit. Icebreaker tankers of the 250,000 DWT size range will have a draft of approximately 24 m (79 ft). Allowing for 3 m (10 ft) of underkeel clearance throughout the tanker's maneuvering area will require that the tanker mooring/loading structure be installed in greater than 27 m (90 ft) water depth. This water depth occurs between 20 and 50 km (12 to 30 mi ) off the Alaskan shoreline throughout most of the Diapir Field region. Therefore, if extensive dredging is to be avoided, the "nearshore" tanker mooring/loading structure must be quite far offshore and the same selection criteria described for offshore terminals in Section 7.3.1 will apply.

Extensive dredging of a channel and basin to permit tankers to approach close to shore has been considered in the past but has been rejected because of extremely high initial and maintenance dredging costs and the uncertainty regarding a tanker's capability to safely negotiate a long channel in Beaufort Sea winter ice conditions (VHA, 1969).

A nearshore terminal would require a long and costly marine pipeline from the production platform to the onshore storage facilities and a large diameter marine pipeline from the storage facilities to the mooring/loading structure. These pipelines must be installed in trenches up to 6 m (20 ft) deep to avoid damage by ice gouging.

Since nearshore terminals offer no significant advantage over offshore terminals and will require a much greater capital investment, nearshore terminals are not considered further in this study.

## 7.5 ARCTIC TANKERS

It has been assumed that icebreaker tankers will transport the crude oil to an ice-free transshipment terminal in the Aleutian Islands or on the Alaska Peninsula. Conventional tankers will then be utilized to transport the crude oil to its final destination. Depending on a number of factors, some of the more important of which include, production rate, location of final destination, cost of transshipment terminal and cost of icebreaker and conventional tankers, it may be more cost effective for the icebreaker tankers to deliver the oil directly to its final destination. However, it is anticipated that the difference in transportation cost between the two alternatives would be slight in most cases and the transshipment terminal alternative was selected to facilitate comparison with pipeline transportation alternatives which will deliver the oil to a warm water terminal on the south coast of Alaska.

### 7.5.1 Selection of Tanker Size

The most economic size tanker for a particular trade depends on a number of factors, the most important of which include: length of trade route, cruising speed in open water and various concentrations and thicknesses of ice, time in port, throughput, physical restrictions along the trade route, periodic drydocking requirements, and terminal limitations. Where a vessel is required to transit ice fields, size and power take on added importance as ice breaking capability is primarily dependent on displacement, power, hull strength and shape. For preliminary analysis, the optimum size tanker for crude oil transportation from the study area may be determined based on the criteria listed below. However, a final selection of the optimum size can only be made after all characteristics of the oil field development scenario have been defined and the above factors evaluated. The preliminary criteria are as follows:

- a minimum of three tankers will be provided on any route to accommodate required shipyard maintenance,
- unit transportation costs generally decrease with increasing tanker size,
- the maximum size tanker will not exceed 250,000 DWT,
- the cargo carrying capacity of a tanker is approximately equal to 95% of the deadweight,
- the average speed of an icebreaker tanker in open water is approximately 20 knots,
- the average speed of an icebreaker tanker in ice concentration exceeding 4 oktas is highly variable depending on concentration and thickness but for purposes of this study has been assumed to be approximately 6 knots,
- the turnaround time at each loading or unloading terminal is 24 hours, and
- the minimum tanker cargo size provided will be the calculated theoretical minimum during the maximum ice

coverage period assuming one tanker is out of service. Thus, for preliminary evaluation, the optimum size tanker is determined from the following formula:

$$D = \frac{P \times R}{0.95\,(N-1)}$$

where: D = deadweight of optimum size tanker;

P = peak crude oil production rate;

R = round trip time during maximum ice coverage period;

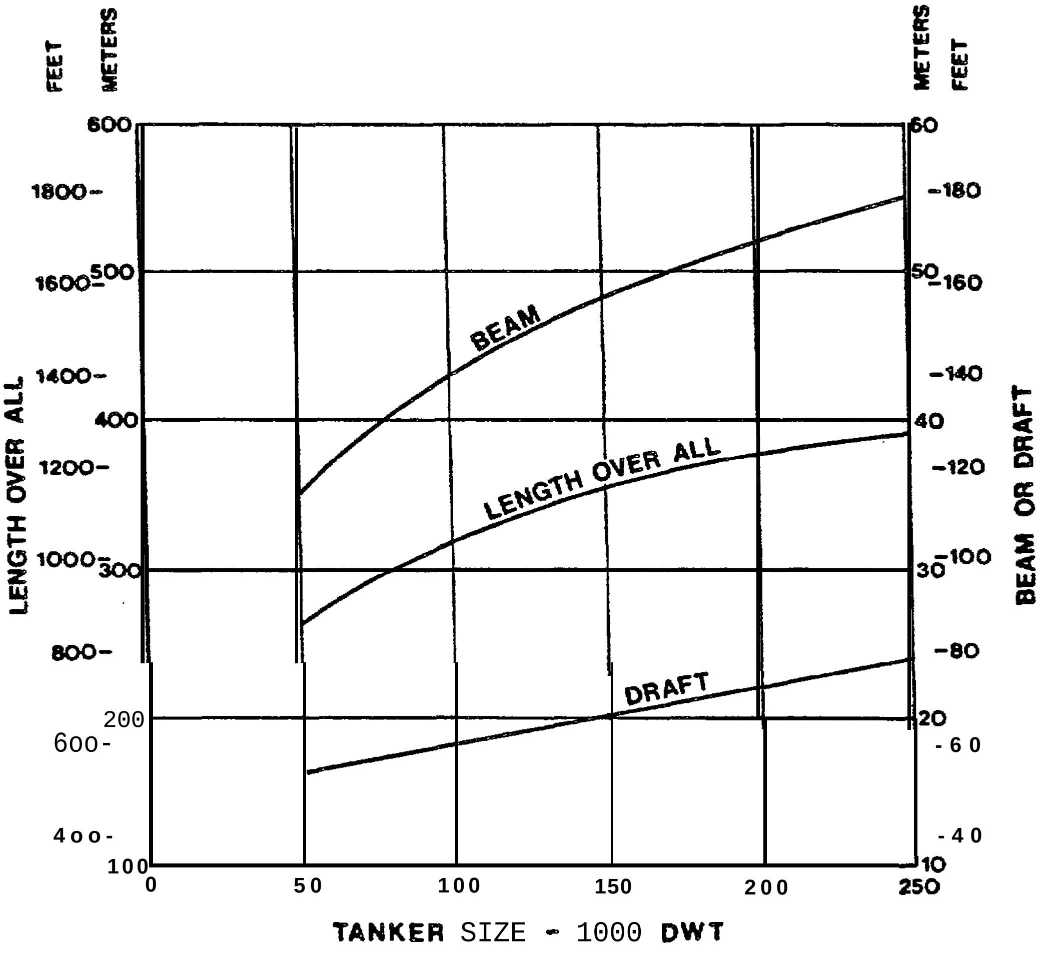
N = number of tankers.

### 7.5.2 Icebreaker Tankers

Tankers servicing an offshore or a nearshore terminal in the Beaufort Sea on a year-round basis must be ice capable. Thus, they will be purpose built and quite different, and thus more expensive than conventional tankers. It has been assumed that the tanker's powering and structural specifications must be equivalent to Canadian Arctic Shipping Pollution Prevention Regulations (CASPPR) Class 8 to permit their continuous operation year-round on westbound routes through the Bering Strait or, alternatively, on eastbound routes via the Northwest Passage. However, industry sources have expressed the opinion that the CASPPR regulations are outdated and overly conservative, especially for determining vessel horsepower, resulting in values up to twice that which are necessary. While it is anticipated that the regulations will be revised, the present version of the regulations has been used for this study. The principal characteristics of the tankers are provided in Figures 7.5-1 and 7.5-2. The tankers may have gas turbine-electric, diesel or, possibly, steam prime movers, or a combination of two of these, and will have 100 percent segregated ballast capacity. Conventional tankers larger than 250,000 DWT are commonly used in petroleum shipping but Arctic-class tankers larger than about 250,000 DWT are considered to exceed current technology, particularly with respect to propulsion machinery, and are not included in the study.

The oil produced in the U.S. Beaufort Sea area is assumed to be transported to ports in the contiguous United States such that U.S.-flag tankers are required to be used by the "Jones Act." Figure 7.5-3 provides the capital cost of Class 8 tankers constructed in the United States. If the oil were to be exported, lower cost foreign-flag tankers could be used.

The performance (speed, voyage time, fuel consumption, etc.) of the tankers in the ice conditions (continuous ice, ridged ice, and broken ice) which exist on each segment. of the voyage for each month during the year and on the open water portions of the voyage has been determined from a computer simulation model (ARTRANS) developed by JJMA (McMullen, 1980). The technical characteristics of the voyages are joined within the model to the financial elements to provide a complete financial analysis of the voyage and the unit transportation cost at a series of speeds. The vessel speed in ice is the maximum



Source: JJ McMullen

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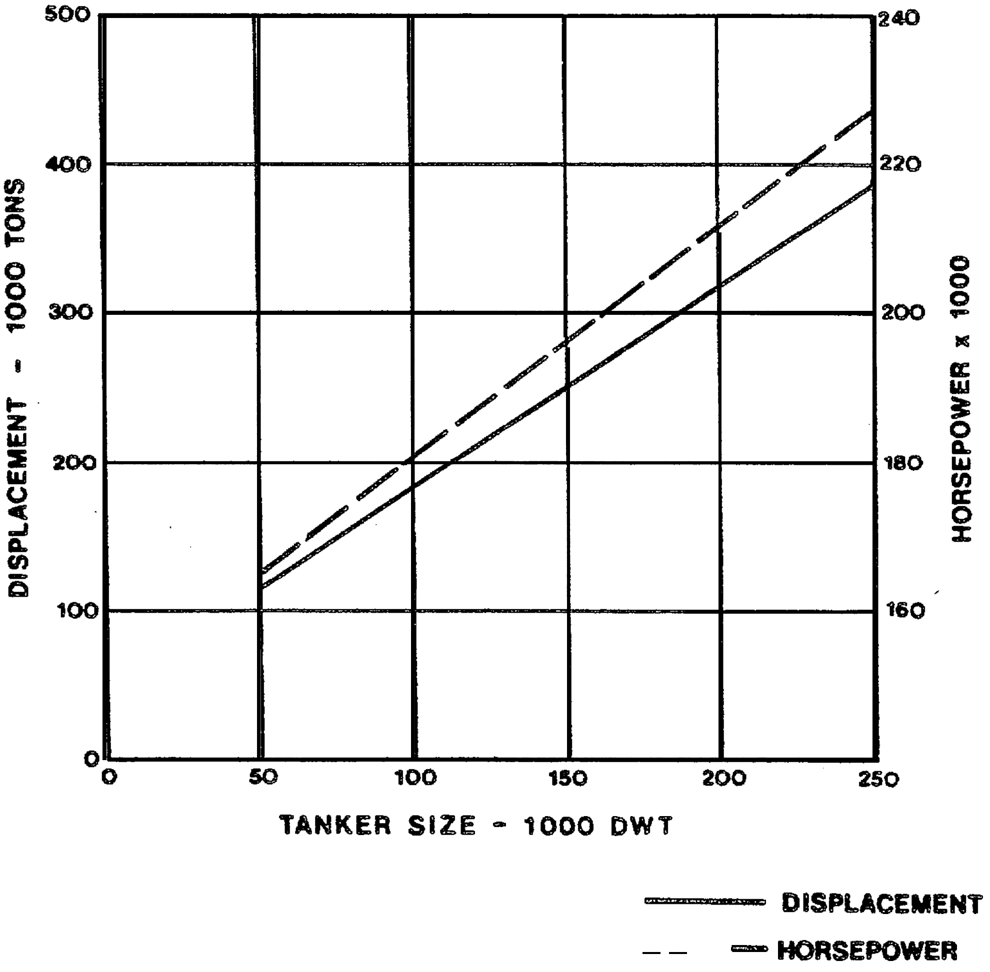
Figure 7.5-1. Dimensions of Class 8 icebreaker tankers.



Source: JJ McMullen

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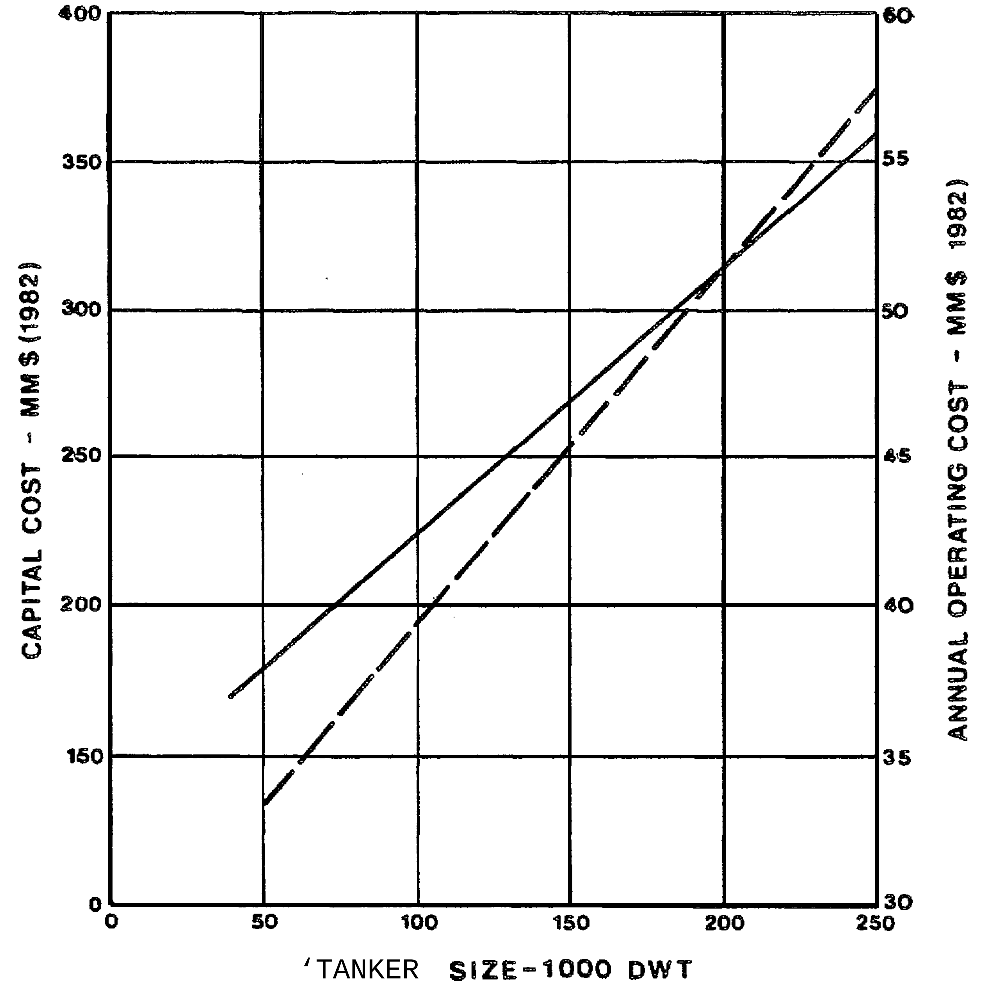
Figure 7.5-2. Displacement and horsepower of Class 8 icebreaker tankers, attainable given the installed propulsion power and ice conditions existing during each month for each voyage segment; the model measures a series of open water speeds and selects that which results in the minimum unit transportation cost for the entire voyage.

Based on the computer model, the estimated annual tanker operating costs were calculated for Arctic-class ships ranging in size from 60,000 to 250,000 DWT. The operating cost estimates are presented in Figure 7.5-3 for the vessels operating to an Alaska Peninsula transsshipment terminal (Balboa Bay) from the center of the Beaufort Sea study area. The estimates reflect vessel performance when operating year-round in the varying ice conditions which prevail from the point of origin to the ice edge in the Bering Sea and in the open water portions of the voyages. Operating costs include 32 man crew, maintenance, insurance, other fixed costs and fuel consumption.

It has been assumed that the tankers will be sufficiently maneuverable to approach an offshore mooring unassisted under most circumstances. During heavy ice conditions a lead will usually be created by the mooring structure as the ice flows past and this lead will aid in guiding the tanker to the mooring. During especially severe conditions an icebreaker will be available to assist in the tanker approach and mooring operations.



Source: JJ McMullen

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Figure 7.5-3. Class 8 Icebreaker tanker capital and annual costs versus tanker size.

### 7.5.3 Submarine Tankers

A 1975 study, "Arctic Submarine Transportation System," prepared by a team headed by Newport News Shipbuilding and Drydock Company (NNSDC, 1975) for the U.S. Maritime Administration was updated by JJMA (McMullen, 1980) by escalating the capital and operating costs so that the unit transportation costs could be compared to those obtained with icebreaking surface tankers. That study found that the design of a submarine tanker for operation under the Arctic ice pack is limited as to the method- of propulsion and to overall size. The primary power source is limited by current technology to use of a nuclear reactor, although fuel cell power plant modules have been suggested as the power source for smaller submarines. The Newport News feasibility study indicated 'that the" one-reactor two-propeller submarine tanker would result in a ship of 200,000 to 300,000 tons deadweight. There is no existing shipyard or facility that could handle the construction and maintenance of a submarine of this size.

For practicality in handling the submarine and in design of the control systems, the submarine tanker would normally cruise at constant depth. The shallowest practicable depth should be selected because structural weight, and thereby cost, increase rapidly with depth of operation. However, the operating depth must be such as to keep it safely below all surface obstructions. Operating depths established for the design were:

Minimum cruising depth - 200 m (650 ft)

Design cruising depth - 215 m (700 ft)

Maximum cruising depth - 230 m (750 ft)

Design collapse depth - 450 m (1,500 ft)

The operating water depths established dictate that the submarine utilize a route under the polar ice cap to a transshipment terminal in Norway or Greenland with conventional tankers utilized for the remainder of the route. Submarine operation through the Chukchi Sea into the Bering Sea would not be possible because of the shallow water depth.

The results of the JJMA study showed that the unit transportation cost of the submarine with a DWT capacity of about 280,000 tonnes is not significantly different than that provided by similar-size icebreaking surface tankers. However, the technical problems associated with loading and unloading these tankers, as well as technical problems regarding a number of construction and operation features, have yet to be solved. The underwater loading terminal must be located in a water depth of 150 m (500 ft) under the polar ice cap. The submarine tanker is generally unaffected by weather and surface ice conditions such that its reliability in maintaining cargo deliverability might be greater than a surface ship, if the many remaining technical problems can be solved.

## 8.0 REFERENCES

Afanas'ev, V.P., Y.V. Dolgopolov and Z.I. Shvaishstein, 1971. Ice Pressure on Individual Marine Structures. Ice Physics and Ice Engineering, G.N. Yakovlev, cd., U.S.S.R., Translation by Israel Program for Science Translation, Israel, 1971.

Agerton, D.J., 1983. Construction of an Arctic Offshore Gravel Island in 39 ft of Water During Winter and Summer. Proceedings Offshore Technology Conference (OTC Paper No. 4548), Houston, May 1983.

Allen, J.L., 1970. Effective Force of Floating Ice on Structures. National Research Council of Canada, Technical Memorandum 98, 1970.

American Petroleum Institute, 1982. API Recommended Practice for Planning, Designing, and Constructing Fixed Offshore Platforms, RP2A, January 1982.

American Petroleum Institute, 1982. API Bulletin on Planning, Designing, and Constructing Fixed Offshore Structures in Ice Environments, Bul 2N, January 1982.

Anderson, D.L., 1958. Preliminary Results and Review of Sea Ice Elasticity and Related Studies. Trans. Eng. Inst. Canada, 2:116-122.

Apelt, C.J. and A. Macknight, 1976. Wave Action on Large Off-Shore Structures. Coastal Engineering Proceedings, Vol. 3, 1976.

APOA Review, Winter 1983/84. Offshore Pipeline Transportation in the Southern Beaufort Sea. Vol. 6 No. 3, Winter 1983/84, pp.31-32.

Arya, S.P.S., 1973. Air Friction and Form Drag on Arctic Sea Ice. AIDJEX Bulletin No. 19, University of Washington, Seattle, 1973.

Assur, A., 1971. Forces in Moving Ice Fields. Proceedings Conference on Port and Ocean Engineering Under Arctic Conditions (POAC), Trondheim, 1971.

Barnes, P.W. and D.M. Hopkins, 1978. Geological Sciences in Environmental Assessment of the Alaska Continental Shelf, Interim Synthesis: Beaufort/Chukchi. NOAA, 1978.

Barnes, P.W. and E. Reimnitz, 1974. Sedimentary Processes on Arctic Shelves off the Northern Coast of Alaska. Proceedings Symposium on Beaufort Sea Coast and Shelf Research, Arctic Institute of North America, December 1974.

Barnes, P.W. and T. Reiss, 1981. Geologic Comparison of Two Arctic Shoals. Environmental Assessment of the Alaskan Continental Shelf, Annual Reports of the Principal Investigators for the Year Ending March 1981 Attachment C, pp.C1-C23.

Bea, R.G., S. Nour-Omid, T.B. Coull, R.E. Potter and H.R. Bivens, 1984. Piling Aids Gravity In Ice Resistance. Offshore, August 1984.

Bechtel, Inc., 1979. Arctic Terminal For Icebreaking Tankers Study, Conceptual Design. Prepared for the U.S. Dept. of Commerce, Maritime Administration, March 1979.

Bertha, F.G. and J.V. Danys, 1975. Prediction of Ice Forces on Conical Offshore Structures. Marine Science Communication, 1975.

Bertha, F.G. and D.G. Stenning, 1979. Arctic Offshore Deepwater Ice-Structure Interactions. Proceedings Offshore Technology Conference (OTC Paper No. 3632), Houston, May 1979.

Berlie, E.M., K. Pullerts and S.G. Sheps, 1984. The Mobile Arctic Island for Drilling and Production. Proceedings Arctic Offshore Technology Conference, Calgary, November 1984.

Bhula, D.N., J.N. Birdy and F.J. Bruen, 1984. Design of Concrete Gravity Structures to Withstand Concentrated Ridge and Floe Impact Loads. Proceedings Offshore Technology Conference (OTC Paper No. 4708), Houston, May 1984.

Blenkarn, K.A., 1970. Measurement and Analysis of Ice Forces on Cook Inlet Structures. Proceedings Offshore Technology Conference (OTC Paper No. 1261), Houston, May 1970.

Blouin, S.E., E.J. Chamberlain, P.V. Sellmann and D.E. Garfield, 1971. Determining Sub-sea Permafrost Characteristics with a Cone Penetrometer - Prudhoe Bay, Alaska. Cold Regions Science and Technology (1971), No. 1.

Boaz, I.B. and D.N. Bhula, 1981. A Steel Production Structure for the Alaskan Beaufort Sea. Proceedings Offshore Technology Conference (OTC Paper No. 4113), Houston, May 1981.

Bow Arctic Resources Brochure, 1984. Mobile Arctic Island for the Beaufort Sea, 1984.

Brower, W.A., Jr., H.W. Searby, J.L. Wise, H.F. Diaz and A.S. Prechtel, 1977. Climatic Atlas of the Outer Continental Shelf Water and Coastal Regions of Alaska; Arctic Environmental Information and Data Center, University of Alaska, 1977.

Brown & Root Development, 1984. Sub-Arctic Deep Water Petroleum Technology Assessment. Alaska OCS Socioeconomic Studies Program, Technical Report No. 109, prepared for the Minerals Management Service, Alaska OCS Region, June 1984.

Bruce, J.C. and A.G. Barrington, 1982. Design Aspects of a Mobile Arctic Caisson. Proceedings Offshore Technology Conference (OTC Paper No. 4333), Houston, May 1982.

Byrd, R.C., R.K. Coleman, R.T. Weiss, I.B. Boaz, E.R. Sauve and R.M. White, 1984. The Arctic Cone Exploration Structure: A Mobile Offshore Drilling Unit for Heavy Ice Cover. Proceedings Offshore Technology Conference (OTC Paper No. 4800), Houston, May 1984.

Cammaert, A.B. and G.P. Tsinker, 1981. Impact of Large Ice Floes and Icebergs on Marine Structures. Proceedings Conference on Port and Ocean Engineering Under Arctic Conditions (POAC), Quebec, 1981.

Cammaert, A.B. and T.T. Wang, 1983. Impact of Sea Ice on Offshore Gravity and Floating Platforms. Proceedings Conference on Port and Ocean Engineering Under Arctic Conditions (POAC), Helsinki, April 1983.

Canada Marine Engineering Ltd., 1982. An Initial Probabilistic Assessment of Ice Loading on Beaufort Sea Structures. CMEL Report No. 1018, prepared for the EIS Partners (Dome, Esso, Gulf).

Chamberlain, E.J., 1983. Frost Heave of Saline Soils. Proceedings International Permafrost Conference, Fairbanks, July 1983.

Chamberlain, E.J., 1979. Overconsolidated Sediments in the Beaufort Sea. The Northern Engineer, Vol. 10, No. 3, Fall 1978.

Chamberlain, E.J., P.V. Sellmann, S.E. Blouin, D.M. Hopkins and R.I. Lewellen, 1978. Engineering Properties of Subsea Permafrost in the Prudhoe Bay Region of the Beaufort Sea. Proceedings International Permafrost Conference, Edmonton, 1978.

Chicago Bridge and Iron Brochure, 1984. Conical Monopod. June 1984.

Chicago Bridge and Iron Brochure, 1984. Portable Arctic Drilling Structure (PADS). June 1984.

Collett, T.S., 1983. Detection and Evaluation of Natural Gas Hydrates from Well Logs, Prudhoe Bay, Alaska. Proceedings International Permafrost Conference, Fairbanks, July 1983.

Corona, E.N. and N. Yashima, 1983. Development of a Novel Ice-Resistant Semi submersible Drilling Unit. Proceedings Offshore Technology Conference (OTC Paper No. 4602), Houston, May 1983.

Cottrill, A., 1982. Oil Tanker Turned Drilling Caisson Brings Revolutionary Concept to Beaufort Sea. Offshore-Engineer, August 1982.

Cox, G.F.N., J.A. Richter, W.F. Weeks and M. Mellor, 1984. A Summary of the Strength and Modulus of Ice Samples from Multi-year Pressure Ridges. Proceedings Offshore Mechanics and Arctic Engineering Symposium, ASME, New Orleans, 1984.

Creager, J.S. and D.A. McManus, 1967. Geology of the Floor of Bering and Chukchi Seas--American Studies. In: The Bering Land Bridge, D.M. Hopkins. Stanford University Press, pp.7-31.

Croasdale, K.R., 1984. The Limiting Driving Force Approach to Ice Loads. Proceedings Offshore Technology Conference (OTC Paper No. 4716), Houston, May 1984.

Croasdale, K.R., 1980. Ice Forces on Fixed, Rigid Structures. Working Group on Ice Forces on Structures, Special Report 80-26, IAHR, Part II, 1980.

Croasdale, K.R., 1975. Ice Forces on Marine Structures. Proceedings IAHR International Symposium on Ice Problems, 1975.

Croasdale, K.R. and R.W. Marcellus, 1978. Ice and Wave Action on Artificial Islands in the Beaufort Sea. Canadian Journal of Civil Engineering, 5-1, 1978.

Croasdale, K.R., N.R. Morgenstern and J.B. Nuttall, 1977. Indentation Tests to Investigate Ice Pressure on Vertical Piers. Journal of Glaciology, Vol. 19, No. 81, 1977.

Croasdale, K.R. and A. Person, 1984. A Logical Approach to Ice Loads. Proceedings Symposium on Arctic Offshore Drilling Platforms, Houston, April 1984.

Croteau, P., 1983. Dynamic Interactions Between Floating Ice and Offshore Structures. Earthquake Engineering Research Center, University of California, UCB/EERC-83/01, 1983.

Croteau, P., M. Rojansky and B.C. Gerwick, 1984. Summer Ice Floe Impacts Against Caisson Type Exploratory and Production Platforms. Proceedings Offshore Mechanics and Arctic Engineering Symposium, ASME, New Orleans, 1984.

Danys, J. V., 1977. On Wind Induced Static Ice Forces on Offshore Structures. Proceedings Conference on Port and Ocean Engineering Under Arctic Conditions (POAC), St. John's, September 1977.

Daoud, N. and S.B. Wetmore, 1984. The Monopod Jackup Platform (MT90) - A Mobile Drilling System for Offshore Arctic Application. Proceedings Symposium on Arctic Offshore Drilling Platforms, Houston, April 1984.

Dickens, D.F., 1979. Study of Ice Conditions Along a Year-Round Shipping Route from the Bering Strait to the Canadian Beaufort Sea. Prepared for Canadian Marine Drilling Ltd., Calgary, 54 pp.

Dingle, P.J., 1982. Constructing Artificial Islands in Canada's Beaufort Sea, June 1982, pp.28-31.

Dunbar, M., 1952. Historical References to Ice Islands. Arctic, Vol. 5, No. 2, pp.83-94.

Dunwoody, A.B., 1983. The Design Ice Island for Impact Against an Offshore Structure. Proceedings Offshore Technology Conference (OTC Paper No. 4550), Houston, May 1983.

Dunwoody, A.B., J.A. Losch and K. Been, 1984. Ice/Berm Interactions. Proceedings Offshore Technology Conference (OTC Paper No. 4672), Houston, May 1984. ,

Dykins, J.E., 1971. Ice engineering: material properties of saline ice for a limited range of conditions. Naval Civil Engineering Lab Technical Report TR720.

Edwards, R.Y. and K.R. Croasdale, 1976. Model Experiments to Determine Ice Forces on Conical Structures. Proceedings Symposium on Applied Glaciology, International Glaciology Society, 1976.

Ehrenbard, R.L., P. Hoekstra and G. Rozenberg, 1983. Transient Electromagnetic Soundings for Permafrost Mapping. Proceedings International Permafrost Conference, Fairbanks, 1983.

Engineering News Record, 1984. Canadians Tap Beaufort - Mobile Island Developed For Arctic Oil Exploration. October 25, 1984, pp.17-18.

Engineering News Record, 1984. Concrete Platform Built of Modules. March 8, 1984, p.16.

Fitzpatrick, J. and D.G. Stenning, 1983. Design and Construction of Tarsiut Island in the Canadian Beaufort Sea. Proceedings Offshore Technology Conference (OTC Paper No. 4517), Houston, May 1983.

Fluor-Doris, Inc. Brochure, 1984. Arctic Composite Platform (ARCOP), 1984.

Forssen, D.K, 1978. Design and Construction of Cellular Islands in Arctic Waters. Proceedings ASCE. Cold Regions Specialty Conference, Anchorage, May 1978, Vol. 1.

Frankenstein, G. and R. Garner, 1967. Equations for Determining the Brine Volume of Sea Ice From -0.5° to -22.9°C, Journal of Glaciology, Vol. 6, No. 48, 1967.

Frederking, R. and L.W. Gold, 1975. Experimental Study of Edge Loading of Ice Plates. Canadian Geotechnical Journal, Vol. 12, No. 4, 1975.

Frederking, R. and J. Schwarz, 1982. Model Tests of Ice Forces on Fixed and Oscillating Cones. Cold Regions Science and Technology,. 6 (1982), pp.61-72.

Gaida, K.P., J.K. Barnes and B.D. Wright, 1983. Kulluk - An Arctic Exploratory Drilling Unit. Proceedings Offshore Technology Conference (OTC Paper No. 4481), Houston, May 1983.

Garrison, C.J., A. Torum, C. Iversen, S. Lievseth and C.C. Ebbesmeyer, 1974. Wave Forces on Large Volume Structures - A Comparison Between Theory and Model Tests. Proceedings Offshore Technology Conference (OTC Paper No. 2137), Houston, May 1974.

Gershunov, E.M., 1984. Shear Strength of Adfreeze Bond and Its Effect on Global Ice Load Applied to Mobile Offshore Drilling Units Under Arctic Conditions. Proceedings Offshore Technology Conference (OTC Paper No. 4687), Houston, May 1984.

Gerwick, B.C., 1983. Oil Rigs Designed to Combat Arctic Ice. Civil Engineering, December 1983, pp.38-41.

Gerwick, B.C. and H.O. Jahns, 1979. Conceptual Design of Floating Drilling, Production and Storage Caisson for Arctic Waters. Proceedings Conference on Port and Ocean Engineering Under Arctic Conditions (POAC), Trondheim, August 1979.

Gerwick, B.C., R.E. Potter, 1-1. Matlock, R. Mast and R. Bea, 1983. Application of Multiple Spuds (Dowels) to Development of Sliding Resistance for Gravity-Base Platforms. Proceedings Offshore Technology Conference (OTC Paper No. 4553), Houston, May 1983.

Gerwick, B.C., R.E. Potter and M. Rojansky, 1984. Development of a Structural Concept to Resist Impacts From Multiyear Ice Floes, Ridges and Icebergs. Proceedings Offshore Technology Conference (OTC Paper No. 4799), Houston, May 1984.

Gladwell, R.W., 1976. Field Studies of Eight First-year Sea Ice Pressure Ridges in the Southern Beaufort Sea. APOA Project 75, Imperial Oil Ltd., IPRT-8ME-76, Calgary, 1976.

Global Marine Engineering Co., 1977. A Preliminary Feasibility Study of a Tanker Transportation System Serving the Northwest Coast of Alaska. Report prepared for the U.S. Department of Commerce, Maritime Administration, Office of Commercial Development.

Good, R.R., K.G. Anderson and H.H. Lanziner, 1984. Ice/Berm Interaction Study Using Rotary Sidescan Sonar and Acoustic Profiling Systems. Proceedings Offshore Technology Conference (OTC Paper No. 4721 ), Houston, May 1984.

Grantz. A. et al., 1982. Geological Framework, Hydrocarbon Potential and Environmental Conditions for Exploration and Development of Proposed Oil and Gas Lease Sale 67 in the Beaufort and Northeast Chukchi Seas. Summary Report, U.S. Department of the Interior, Geological Survey, 45 pp. Open File Report 82-482.

Grantz, A., S. Eittreim and O.T. Whitney, 1981. Geology and Physiography of the Continental Margin North of Alaska and Implications for Origin of the Canada Basin, in Nairn, A.E.M.; M. Churkin, Jr. and F.G. Stehli, eds., The Ocean Basins and Margins, v. 5, pp.439-492.

Greta, A.D., 1984. New Concepts of Offshore Drilling/Production Arctic Platform and Dynamic Analysis of the Fast Removal Operation. Proceedings IMAE Symposium, 1984, Vol. 3.

Greely, A.W., 1886. Three Years of Arctic Service. An Account of the Lady Franklin Bay Expedition of 1881-84. New York: Vol. 1, 428 pp., Vol. 2, 444 pp.

Greenaway, K.R., 1952. Additional Information From Flights and Air Photographs in the Canadian Arctic. Arctic, Vol. 5, No. 2, pp.75-82.

Hancock, J.A., T.A. Hudson, P.H. Van Scherpe and R.E. Steddum, 1979. Preliminary Design of the Arctic Mobile Drilling Structure. Proceedings Conference on Port and Ocean Engineering Under Arctic Conditions (POAC), Trondheim, August 1979.

Han-Padron Associates, 1984. Evaluation of Bering Sea Crude Oil Transportation Systems. Alaska OCS Socioeconomic Studies Program, Technical Report No. 110, prepared for the Minerals Management Service, Alaska OCS Region, July 1984.

Hartz, R.W. and D.M. Hopkins, 1980. A Review of Offshore Permafrost Studies, Beaufort Sea, Alaska, 1976 to 1979 In: Offshore Permafrost and Shoreline History as an Aid to Predicting Offshore Permafrost Conditions. Environmental Assessment of the Alaskan Continental Shelf. Annual Reports. National Oceanic and Atmospheric Administration, Department of Commerce, Washington, DC.

Hetenyi, M., 1946. Beams on Elastic Foundations. University of Michigan Press, 1946.

Hibler, W.D., 1980. Modelling a Variable Thickness Sea Ice Cover. Monthly Weather Review, Vol. 108, No. 12, 1980.

Hibler, W.D., 1975. Statistical Variations in Arctic Sea Ice Ridging and Deformation Rates. Proceedings Sot. Naval Arch. Mar. Eng. Symposium on Ice Breaking and Related Technology, Montreal, April 1975.

Hibler, W.D. and S.F. Ackley, 1973. A Sea Ice Terrain Model and Its Application to Surface Vehicle Trafficability. CRREL Report 314, 21 pp.

Hibler, W.D., W.F. Weeks and S.J. Mock, 1972. Statistical Aspects of Sea Ice Ridge Distributions. J. Geophysics Res. 77:5954-5970.

Hogben, N. and R.G. Standing, 1974. Wave Loads on Large Bodies. International Symposium on the Dynamics of Marine Vehicles and Structures in Waves, Institute of Mechanical Engineer%, 1974.

Hopkins, D.M., 1978. Effects of Gravel Mining and Construction of Gravel Islands and Causeways in Environmental Assessment of the Alaskan Continental Shelf. Interim Synthesis: Beaufort/Chukchi, NOAA, 1978.

Isaacson, M., 1981. Steep Wave Effects on Large Offshore Structures. Proceedings Offshore Technology Conference (OTC Paper No. 3955), Houston, May 1981.

Isaacson, M. and S. Wu, 1984. Shallow Wave Forces on Offshore Structures. Proceedings Offshore Technology Conference (OTC Paper No. 4810), Houston, May 1984.

Jazrawi, W. and J. Khanna, 1977. Monotone - A Mobile Gravity Platform for the Arctic Offshore. Proceedings Conference on Port and Ocean Engineering Under Arctic Conditions (POAC), St. John's, September 1977.

Jeffries, M.O., 1983a. Preliminary Isotope Studies on Ward Hunt Ice Shelf. Defense Research Establishment Pacific, Contractors Report 83-26.

**Jeffries,** M. O., **1983b.** Arctic Ice Shelf Studies, Spring 1983. Defense Research Establishment Pacific, Contractors Report 83-27.

**Jeffries,** M.O., **1983c.** Isotope Variations in Ice Cores from Ward Hunt Ice Shelf and Milne Ice Shelf, Ellesmere Island, NWT. Defense Research Establishment Pacific, Contractors Report 83-56.

**Jeffries, M.O.** and H. **Serson,** 1983. Recent Changes at the Front of Ward Hunt Ice Shelf, Ellesmere Island, N.W.T. Arctic, Vol. 36, No. 3, pp.287-290.

Jong, J.J.A. de and J.C. Bruce. Design and Construction of Caisson Retained Island Drilling Platform for Beaufort Sea. Proceedings Offshore Technology Conference (OTC Paper No. 3297), Houston, May 1978.

Judge, A., 1982. Natural Gas Hydrates in Canada. Proceedings Canadian Permafrost Conference, Calgary, March 1981.

Karp, L.B. 1980. Concept Development of a Concrete Structure Founded in the Ice-stressed Chukchi Sea: A Case of Ice/Structure Interaction in an Offshore Arctic Region. Dept. of Civil Engineering, University of California, Berkeley.

**Katona, M.G.** and K.D. Vaudrey, 1973. Ice Engineering: Summary of Elastic Properties Research and Introduction to Visoelastic and Nonlinear Analysis of Saline Ice. Naval Civil Engineering Lab Technical Report R797, 67 pp.

**Kliewer,** R.M. and G.A. Forbes, 1980. A Fixed Platform Providing An Integrated Deck on a Multiple Leg Ice Resistant Substructure. Proceedings Offshore Technology Conference (OTC Paper No. 3886), Houston, May 1980.

**Kokkinowrachos,** K. and H. Wilckens, 1974. Hydrodynamic Analysis of Cylindrical Offshore Oil Storage Tanks. Proceedings Offshore Technology Conference (OTC Paper No. 1944), Houston, May 1974.

**Korzhavin,** K.N., 1962. Action of Ice on Engineering Structures. U.S.S.R. Academy of Science, Siberian Branch, 1962 (CRREL Translation 260, 1971).

Kotras, T.V., C.L. Arnold and K.M. Bergman, 1983. Strength of Gravel Islands to Resist Ice Loads. Proceedings Offshore Technology Conference (OTC Paper No. 4549), Houston, May 1983.

**Kovacs,** A., 1983. Characteristics of Multi-Year Pressure Ridges. Proceedings Conference on Port and Ocean Engineering Under Arctic Conditions (POAC), Helsinki, April 1983.

Kozo, T.L. and O.I. Diachok, 1973. Spatial Variability of Topside and Bottomside Ice Roughness and its Relevance to Underside Acoustic Reflection Loss. AIDJEX Bulletin 19:113-121.

Kry, P.R., 1980. Ice Forces on Wide Structures. Canadian Geotechnical Journal, Vol. 17, February 1980, pp.97-113.

Kry, P.R., 1978. A Statistical Prediction of Effective Ice Crushing Stresses on Wide Structures. Proceedings IAHR Ice Symposium, 1978.

LaBelle, J.C., 1973. Fill Materials and Aggregate Near Barrow, Naval Petroleum Reserve No. 4, Alaska. Office of Naval Petroleum and Oil Shale Reserves, January 1973.

LaBelle, J.C., J.L. Wise, R.P. Voelker, R.H. Schulze and G.M. Wohl, 1983. Alaska Marine Ice Atlas; Arctic Environmental Information and Data Center, University of Alaska.

Lachenbruch, A.H. and B.V. Marshall, 1977. Sub-Sea Temperatures and a Simple Tentative Model for Offshore Permafrost at Prudhoe Bay, Alaska. U.S. Dept. of the Interior Geological Survey, Open-File Report 77-395, April 1977.

Lachenbruch, A.H., J.H. Sass, L.A. Lawver, M.C. Brewer and T.H. Moses, Jr., 1982. Depth and Temperature of Permafrost on the Alaskan Arctic Slope; Preliminary Results. U.S. Geological Survey Open-File Report 82-1039, 1982.

Lamp, The (published by Exxon Corp.), 1982. Technology for Tackling Alaska's Oil. Fall 1982.

Langleben, M.P. and E.R. Pounder, 1963. Elastic Parameters of Sea Ice, pp.69-78. In: W.D. Kingery (cd.), Ice and Snow: Processes, Properties, and Applications, MIT Press, Cambridge.

Leshack, L., 1980. Arctic Ocean Sea Ice Statistics Derived From the Upward-Looking Sonar Data Recorded During Five Nuclear Submarine Cruises. Report to the Office of Naval Research, September 1980.

Lewellen, R.I., 1974. Offshore Permafrost of Beaufort Sea, Alaska. Proceedings Symposium on Beaufort Sea Coast and Shelf Research, Arctic Institute of North America, December 1974.

Lewis, J.W. and K.R. Croasdale, 1978. Modeling the Interaction Between Pressure Ridges and Conical Shaped Structures. Proceedings IAHR Ice Symposium, 1978.

Lob, J.K.S., 1984. A Project Management Approach to Design and Construction of a New Generation Arctic Drilling System. Proceedings Offshore Technology Conference (OTC Paper No. 4704), Houston, May 1984.

Lob, J.K.S., J.C. Stanberg and K.P. Cusack, 1984. New Generation Arctic Drilling System: Overview of First Year's Performance. Proceedings Offshore Technology Conference (OTC Paper No. 4797), Houston, May 1984.

Loken, A.E. and O.A. Olsen, 1976. Diffraction Theory and Statistical Methods to Predict Wave Induced Motions and Loads for Large Structures. Proceedings Offshore Technology Conference (OTC Paper No. 2502), Houston, May 1976.

Luk, C.H., 1983. Added Mass and Damping for Ice Floes by Long Water Wave Theory. Proceedings Offshore Technology Conference (OTC Paper No. 4458), Houston, May 1983.

Lyon, W., 1967. Undersurface Profiles of Sea Ice Observed by Submarine. Physics of Snow and Ice; Conference of Low Temperature Science, Hokaido Univ., Sapporo, Japan, Vol. 1, pp.707-711.

Maattanen, M., 1983. Dynamic Ice-Structure Interaction During Continuous Crushing. CRREL Report 83-5, February 1983.

Mancini, C.V., B.E. W. Dowse and J.M. Chevalier, 1983. Caisson Retained Island for Canadian Beaufort Sea - Geotechnical Design and Construction Considerations. Proceedings Offshore Technology Conference (OTC Paper No. 4581), Houston, May 1983.

Marcellus, R.W. and A.C. Palmer, 1979. Shore Crossing Techniques for Offshore Pipelines in Arctic Regions. Proceedings Conference on Port and Ocean Engineering Under Arctic Conditions (POAC), Trondheim, August 1979.

McKenzie, M.B. and B.M. Johansson, 1979. Marine Transportation of Arctic Hydrocarbons. Proceedings Offshore Technology Conference (OTC Paper No. 3631 ), Houston, May 1979.

McMullen, John J. Associates, Inc., 1980. National Petroleum Reserve-Alaska; Marine Transportation System Analysis, Maritime Administration, U.S. Department of Commerce. Washington, D.C.

Mellor, M., 1983. Mechanical Behavior of Sea Ice. U.S. Army CRREL Monograph 83-1, 1983.

Michel, B. and N. Toussaint, 1977. Mechanisms and Theory of Indentation of Ice Plates. Journal of Glaciology, Vol. 19, No. 81, 1977.

Miller, D.L. and D.E. Bruggers, 1980. Soil and Permafrost Conditions in the Alaskan Beaufort Sea. Proceedings Offshore Technology Conference (OTC Paper No. 3887), Houston, May 1980.

Mitsui Engineering & Shipbuilding Co., Ltd. Brochure, 1984. Mitsui Egg-Shaped Ice-Resistant Drill Barge, October 1984.

Mitsui Engineering & Shipbuilding Co., Ltd. Personal Communication, 1984. Concept of Ice Resistant Structure. October 1984.

Mock, S.J., A.D. Hartwell and W.D. Hibler, 1972. Spatial Aspects of Pressure Ridge Statistics. J. Geophysics Res. 77:5945-5953.

Mohr, H.O., 1984. 1,000 New Subsea Completions Expected by 1994. Ocean Industry, November 1984, pp.15-16.

Morack, J.L. and J.C. Rogers, 1982. Marine Seismic Refraction Measurements of Near-shore Subsea Permafrost. Proceedings Canadian Permafrost Conference, 1982.

Myers, J.J., C.H. Helm and R.F. McAllister, 1969. Handbook of Ocean and Underwater Engineering. McGraw-Hill, New York.

National Academy Press, 1982. Understanding the Arctic Sea Floor for Engineering Purposes, 1982.

National Petroleum Council, 1981. U.S. Arctic Oil and Gas. Washington, D.C., December 1981.

Neave, K.G. and P.V. Sellmann, 1983. Seismic Velocities and Subsea Permafrost in the Beaufort Sea, Alaska. Proceedings International Permafrost, Conference, Fairbanks, July 1983.

Neave, K.G. and P.V. Sellmann, 1982. Subsea Permafrost in Harrison Bay, Alaska. CRREL, Report 82-24.

Neill, C.R., 1976. Dynamic Ice Forces on Piers and Piles - An Assessment of Design Guidelines in the Light of Recent Research. Canadian Journal of Civil Engineering, Vol. 3, No. 2, 1976.

Nevel, D.E., 1983. Pressure Ridge Forces. Proceedings Conference on Port and Ocean Engineering Under Arctic Conditions (POAC), Helsinki, April 1983.

Nevel, D.E., et al., 1972. The Ultimate Failure of Floating Ice Sheets. Proceedings of IAHR Symposium, 1972.

Newport News Shipbuilding and Drydock Company, 1975. Maritime Submarine Transportation System Conceptual Design Study, prepared for the U.S. Department of Commerce, Maritime Administration, Office of Commercial Development, January 1975.

Nixon, J. F., 1982. Field Frost Heave Predictions Using the Segregation Potential Concept. Canadian Geotechnical Journal, Vol. 19, Number 4, 1982, pp.526-529.

Ocean Industry, 1984. Arctic Drilling Systems, December 1984, p.83.

Ocean Industry, 1983. Drilling Unit Made of Converted Tanker Hull. November 1983, pp.13-15.

Ocean Industry, 1983. Using Ice Roads to Construct Gravel Islands, November 1983, pp.46-47.

Ocean Industry, 1982. New Drilling Island Concepts For Beaufort Sea, June 1982, pp.32-33.

Ocean Industry, 1981. Ice Maiden. August, 1981, pp.152-157.

Ocean Industry, 1980. Ice Drilling Barge. April 1980, p.461.

OCSEAP, 1978. Environmental Assessment of the Alaskan Continental Shelf, Interim Synthesis: Beaufort/Chukchi. National Oceanic and Atmospheric Administration, Department of Commerce, Washington, D.C.

Offshore, 1984. Hybrid Designed For Shallow Arctic Operations, November 1984, p.106.

Offshore, 1984. New Arctic Mobile Rig Design Completed, November 1984, p.84.

Offshore, 1982. Global Marine Designs Rigs For Arctic Work, December 1982, pp.86-95.

Offshore Engineer, 1984. Composite Construction Shows Promise For Arctic Platforms. November 1984, p.75.

Offshore Engineer, 1983. Arctic Review. January 1983, p.32.

Offshore Engineer, 1982. Caisson Heralds New Approach To Arctic Island Construction. August 1982, pp.28-29.

Offshore Engineer, 1982. Egg-Shaped Drilling Platform Leads Arctic Drive, September 1982, pp.46-47.

Offshore Engineer Arctic Supplement, 1981. Novel Drillship. August 1981, p.30.

Offshore Petroleum: A Business Opportunities Program, Phase II, Volume 4. April 1981.

Oil and Gas Journal, 1983. Canada Logs Progress in Beaufort Operations. January 3, 1983.

Oksanen, P., 1980. Coefficient of Friction between Ice and some Construction Materials, Plastics, and Coatings. Report 7, Laboratory of Structural Engineering, Technical Research Centre of Finland, 77 pp.

Osterkamp, T.E. and W.D. Harrison, 1982. Temperature Measurements in Subsea Permafrost Off the Coast of Alaska. Proceedings Canadian Permafrost Conference, 1982.

Osterkamp, T.E. and W.D. Harrison, 1977. Results of 1975 Drilling Experiment at Prudhoe Bay. Proceedings Symposium on Permafrost Geophysics, October 1976, Technical Memorandum No. 119.

Padron, D.V., F. Joneidi and J.F.Nixon, 1984. A Deepwater Actively Frozen Seabed (DAFS) Drilling/Production Structure for the Beaufort Sea. Proceedings Offshore Technology Conference (OTC Paper No. 4705), Houston, May 1984.

Paige, R.A. and C.W. Lee, 1967. Preliminary Studies on Sea Ice in McMurdo Sound, Antarctica, during "Deep Freeze 65". J. Glaciol., 6:515-528.

Parmerter, R.R. and M.D. Coon, 1973. On the Mechanics of Pressure Ridge Formation in Sea Ice. Proceedings Offshore Technology Conference (OTC Paper No. 1810), Houston, May 1973.

Parry, W.E., 1821. Journal of a Voyage for the Discovery of a North-West Passage from the Atlantic to 'the Pacific, Performed in the Years 1819-20. London, 310 pp.

Pearce, J.C. and G.E. Strickland, 1979. Ice Forces on Conical Structures. Proceedings Offshore Technology Conference, (OTC Paper No. 3635), Houston, May 1979.

Peary, R.E., 1907. Nearest the Pole. A Narrative of the Polar Expedition of the Peary Arctic Club in the S. S. Roosevelt, 1905-1906, London, 410 pp.

Person, A., 1984. Concrete Island Production System (CIPS), An Arctic Production Platform. Proceedings Symposium on Arctic Offshore Drilling Platforms, Houston, April 1984.

Prager, B.T., 1983. Digital Signal Processing of UHF Radio Echo Sounding Data from Northern Ellesmere Island. M.S. Thesis, University of British Columbia.

Pritchard, R.S., 1977. The Effect of Strength on Simulations of Sea Ice Dynamics. Proceedings Conference on Port and Ocean Engineering Under Arctic Conditions (POAC), St. John's, September 1977.

Prodanovic, A., 1979. Model Tests of Ice Rubble Strength. Proceedings Conference on Port and Ocean Engineering Under Arctic Conditions (POAC), Trondheim, August 1979.

Queenan, C.F., 1984. Los Angeles Ice Cutter Aims at Year Round Drilling Unit Mobility. The Pacific Maritime Magazine, November 1984, p.24-25.

Ralston, T.D., 1979. Sea Ice Loads. Technical Seminar on Alaskan Beaufort Sea Gravel Island Design, Exxon Co. USA, Anchorage, October, 1979.

Ralston, T.D., 1978. An Analysis of Ice Sheet Indentation. International Association of Hydraulic Research Ice Symposium, 1978.

Ralston, T.D., 1977a. Ice Force Design Considerations for Conical Offshore Structures. Proceedings Conference on Port and Ocean Engineering Under Arctic Conditions (POAC), St. John's, September 1977.

Ralston,T.D., 1977b. Yield and Plastic Deformation in Ice Crushing Failure. ICSI/AIDJEX Symposium on Sea Ice - Processes and Models, 1977.

Ramsden, H.D., 1984. Arctic Alaska Offshore Drilling. STAR Symposium, Los Angeles, April 1984.

Reed, J.C. and J.E. Slater, 1974. The Coast and Shelf of the Beaufort Sea. The Arctic Institute of North America, Arlington, Virginia.

Reimnitz, E., P.W. Barnes and R.L. Phillips, 1984. Geological Evidence for Sixty Meter Deep Pressure Ridge Keels in the Arctic Ocean. IAHR Ice Symposium, Hamburg, Vol. 2, pp.189-206.

Reimnitz, E. and K.F. Bruder, 1972. River Discharge into an Ice-Covered Ocean and Related Sediment Dispersal, Beaufort Sea, Coast of Alaska. Geological Society of America Bulletin, Vol. 83, pp.861-866, March 1972.

Reimnitz, E. and E. Kempema, 1981. Pack Ice Interaction with Stamukhi Shoal, Beaufort Sea, Alaska. Environmental Assessment of the Alaskan Continental Shelf, Annual Report of the Principal Investigators for the Year Ending March 1981, Boulder, CO, U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Outer Continental Shelf Environmental Assessment Program, Attachment F, pp.F1-F24.

Reimnitz, E. and D. Maurer, 1978. Stamukhi Shoals of the Arctic--Some Observations from the Beaufort Sea. Open File Report 78-666, U.S. Department of the Interior, 17 pp.

Reimnitz, E., C.A. Rodeick and S.C. Wolf, 1974. Strudel Scour: A Unique Arctic Marine Geologic Phenomenon. The Society of Economic Paleontologists and Mineralogists, 1974.

Reimnitz, E., L.J. Toimil and P.W. Barnes, 1977. Stamukhi Zone Processes: Implications for Developing the Arctic Offshore. Proceedings Offshore Technology Conference (OTC Paper No. 2945), Houston, May 1977.

Richter, J.A. and G.F.N. Cox, 1984. A Preliminary Examination of the Effect of Structure on the Compressive Strength of Ice Samples from Multi-year Pressure Ridges. Proceedings Offshore Mechanics and Arctic Engineering Symposium, ASME, New Orleans, 1984.

Rodeick, C.A., 1974. Marine Gravel Deposits of the Beaufort Sea Shelf. Proceedings of Symposium on Beaufort Sea Coast and Shelf Research, Arctic Institute of North America, December 1974.

Rogers, J.C., 1977. Seismic Investigation of Offshore Permafrost Near Prudhoe Bay, Alaska. Proceedings Symposium on Permafrost Geophysics, October 1976, Technical Memorandum No. 119.

Rogers, J.C. and J.L. Morack, 1978. Geophysical Investigation of Offshore Permafrost, Prudhoe Bay, Alaska. Proceedings International Permafrost Conference, Edmonton, 1978.

Rothrock, D.A., 1975. The Energetic of Plastic Deformation of Pack Ice by Ridging. J. Geophys. 80, 1975, pp.4514-4519.

Russell, W.E., W. Bobby, F. Joneidi, D.V. Padron and N.P. Riggs, 1983. Structural Integrity of Concrete Production Platforms for Hibernia. Proceedings Conference on Canadian Offshore Drilling and Downhole Technology, Edmonton, September 1983.

Sackinger, W.M., W.J. Stringer and H. Serson, 1984. Arctic Ice Island and Sea Ice Movements and Mechanical Properties. Second Quarterly Report to U.S. Dept. of Energy, Geophysical Institute, University of Alaska, 1984.

Sackinger, W.M. and W.J. Stringer, 1983. Arctic Ice Island and Sea Ice Movements and Mechanical Properties. First Quarterly Report to U.S. Dept. of Energy, Geophysical Institute, University of Alaska, 1983.

Saeki, H., T. One, N. Nakazawa, M. Saki and S. Tanaka, 1984. The Coefficient of Friction Between Sea Ice and Various Materials Used in Offshore Structure. Proceedings Offshore Technology Conference (OTC Paper No. 4689), Houston, May 1984.

Saeki, H., T. Ono and A. Ozaki, 1979. Experimental Study on Ice Forces on Cone-Shaped and Inclined Pile Structures. Proceedings Conference on Port and Ocean Engineering Under Arctic Conditions (POAC ), Trondheim, August 1979.

Saeki, H., S. Tanaka and T. One, 1984. The Distribution of Ice Pressure on Offshore Pile Structure and the Failure Mechanics of Ice Sheet. Proceedings Offshore Technology Conference (OTC Paper No. 4686), Houston, May 1984.

Sangrey, D.A., E.C. Clukey and F. Molnia, 1979. Geotechnical Engineering Analysis of Underconsolidated Sediments from Alaska Coastal Waters. Proceedings Offshore Technology Conference (OTC Paper No. 3436), Houston, May 1979.

Schwarz, J., K. Hirayama and H.C. Wu, 1974. Effect of Ice Thickness on Ice Forces. Proceedings Offshore Technology Conference, (OTC Paper No. 2048), Houston, May 1974.

Schwarz, J. and W.F. Weeks, 1977. Engineering Properties of Sea Ice. J. Glaciol., 19:499-531.

Sea Log Corporation Brochure. Principal Characteristics of Sea Log Arctic Offshore Drilling Systems, 1984.

Sellmann, P.V., 1980. Regional Distribution and Characteristics of Bottom Sediments in Arctic Coastal Waters of Alaska. U.S. Army Corps of Engineers, CRREL, Hanover, N.H., Special Report 80-15.

Sellmann, P.V. and E.J. Chamberlain, 1980. Permafrost Beneath the Beaufort Sea: Near Prudhoe Bay, Alaska. Journal of Energy Resources Technology, ASME, March 1980, Vol. 102/35.

Sellmann, P.V. and E.J. Chamberlain, 1979. Permafrost Beneath the Beaufort Sea: Near Prudhoe Bay, Alaska. Proceedings Offshore Technology Conference (OTC Paper No. 3527), Houston, May 1979.

Sellmann, P.V., E. Chamberlain, S.E. Blouin, I.K. Iskandar and R.I. Lewellen, 1976. Field Methods and Preliminary Results From Subsea Permafrost Investigations in the Beaufort Sea, Alaska. Proceedings Symposium on Permafrost Field Methods and Permafrost Geophysics, October 1977, Technical Memorandum No. 124.

Sellmann, P.V. and D.M. Hopkins, 1984. Subsea Permafrost Distribution on the Alaskan Shelf. Proceedings Permafrost Conference, Fairbanks, July 1983, Vol. 2, Panel Discussion.

Sisodiya, R.G. and K.D. Vaudrey, 1981. Beaufort Sea First-Year Ice Features Survey-1979. Proceedings Conference on Port and Ocean Engineering Under Arctic Conditions, Quebec, 1981.

Skjelbreia, L., 1979. Wave Forces on Large North Sea Gravity Structures. Civil Engineering in the Oceans IV, Vol. 1, 1979.

Smith, S.D. and E.G. Banke, 1973. Wind Stresses on Arctic Sea Ice. AIDJEX Bulletin No. 18, University of Washington, Seattle, 1973.

Sodhi , D.S. and C.E. Morris, 1984. Dependence of Crushing Specific Energy on the Aspect Ratio and the Structure Velocity. Proceedings Offshore Technology Conference (OTC Paper No. 4688 ), Houston, May 1984.

Sonat Offshore Drilling Brochure, 1984. Sonat Hybrid Arctic Drilling Structure - SHADS. 1984.

Sorensen, C., 1977. Dynamic Bending Failure of a Semi-Infinite Ice Floe Hitting A Sloping Plane. Progress Report, ISVA, Technical University of Denmark, 1977.

Stenning, D.G. and C.G. Schumann, 1979. Arctic Offshore Deepwater Ice Structure Interactions. Proceedings Offshore Technology Conference (OTC Paper No. 3630), Houston, May 1979.

Stewart, H.R.,M.G. Jefferies and H.M. Goldby, 1983. Berm Construction for the Gulf Canada Mobile Arctic Caisson. Proceedings Offshore Technology Conference (OTC Paper No. 4552), Houston, May 1983.

Stringer, W.J. and S.A. Barrett, 1975. Ice Motion in the Vicinity of a Grounded Floeberg. Proceedings Conference on Port and Ocean Engineering Under Arctic Conditions, Fairbanks, 1975.

Swift, R. and J. Dixon, 1983. Design Wave and Design Force Estimation for Shallow-water Offshore Structures. Proceedings Offshore Technology Conference (OTC Paper No. 4614), Houston, May 1983.

Swift, D.W., W.D. Harrison and T.E. Osterkamp, 1983. Heat and Salt Transport Processes in Thawing Subsea Permafrost at Prudhoe Bay, Alaska. Proceedings International Permafrost Conference, Fairbanks, July 1983.

Tart, R.G. and J.M. Colonell, 1984. Construction Monitoring of Beaufort Sea Exploration Islands. Proc. Cold Regions Spec. Conf. ASCE/CSCE, April 1984, Edmonton, pp.343-349.

Thompson, C.J., H.J. Coleman, J.E. Dooley and D.E. Hirsch, 1971. Bumines Analysis Shows Characteristics of Prudhoe Bay Crude. Oil and Gas Journal, October 5, 1971.

Torum, A., P.K. Larsen and P.S. Hafskjold, 1974. Offshore Concrete Structures - Hydraulic Aspects. Proceedings Offshore Technology Conference (OTC Paper No. 1947), Houston, May 1974.

Traetteberg, A., L. W. Gold and R. Frederking, 1975. The Strain Rate and Temperature Dependence of Young's Modulus of Ice. Proceedings Symposium on Ice Problems, IAHR, Hanover, 1975, pp.479-486.

Tubb, M., 1971." New Concept: Arctic Offshore Drilling System. Ocean Industry, June 1971, pp.55.

Tucker, W.B. and J. Govoni, 1981. Morphological Investigations of First-Year Sea Ice Pressure Ridge Sails. Cold Regions Sci. Tech.

Tusima, K. and T. Tabata, 1979. Friction measurements of sea ice on flat plates of metals, plastics, and coatings, 1:741-755. Proceedings Conference on Port and Ocean Engineering under Arctic Conditions (POAC), Trondheim, August 1979.

Use Department of the Interior, Biological Services Program, 1980. Gravel Removal Studies in Arctic and Subarctic Floodplains in Alaska, FWS/OBS-80/08, June 1980.

Use Department of the Interior, Bureau of Land Management, Alaska OCS Office, 1979. Beaufort Sea Final Environmental Impact. Statement, Anchorage.

Us. Department of the Interior, Bureau of Land Management, Alaska OCS Office, 1982. Diapir Field Final Environmental Impact Statement, Proposed Oil and Gas Lease Sale 71, Anchorage.

U.S. Department of the Interior,. Minerals Management Service. Alaska OCS Region, March 1984. Final Environmental Impact Statement, Diapir Field Lease Offering, June 1984.

Van Houten Associates, 1969. Engineering Study Arctic Marine Terminal Facilities. Prepared for Esso Research and Engineering Company, November 1969.

Vaudrey, K.D., 1979. Preliminary Field Information from AOGA Project 55.

Vaudrey, K.D., 1977. Determination of Mechanical Sea Ice Properties by Large-Scale Field Beam Experiments. Proceedings Conference on Port and Ocean Engineering Under Arctic Conditions (POAC), St. John's, September 1977.

Vivatrat, V. and J.R. Kreider, 1981. Ice Force Prediction Using a Limited Driving Force Approach. Proceedings Offshore Technology Conference (OTC Paper No. 4115), Houston, May 1981.

Vivatrat, V. and S. Slomski, 1983. A Probabilistic Basis for Selecting Design Ice Pressures and Ice Loads for Arctic Offshore Structures. Proceedings Offshore Technology Conference (OTC Paper No. 4457), Houston, May 1983.

Voelker, R.P., T. Brennan and C.W. Parker, 1981a. Evaluating Commercial Arctic Marine Transportation with Polar Class Icebreakers. Proceedings SNAME Spring Meeting/STAR Symposium, Ottawa, June 1981.

Voelker, R.P., F.W. DeBord, F.A. Geisel, J.L. Coburn and K.E. Dane, 1981b. Winter 1981 Trafficability Tests of the USCGC Polar Sea, Vol. II, Environmental Data, Report No. 583C-3 to Maritime Administration, Arctec, Inc., Columbia, 1981.

Voelker, R.P., F.A. Geisel, K.E. Dane, G.M. Wohl and R.S. Shelsby, 1983. Arctic Deployment of USCGC Polar Sea-Winter 1983. Vol. II, Environmental Data, Report No. 868, Arctec, Inc., Columbia, 1981.

Wadhams, P., 1983. Arctic Sea Ice Morphology and 'its Measurements. Proceedings Arctic Technology and Policy Conference, M.I.T., Cambridge.

Wadhams, P., 1980. A Comparison of Sonar and Laser Profiles Along Corresponding Tracks in the Arctic Ocean. In: R.S. Pritchard (cd) Sea Ice Processes and Models, University of Washington Press, Seattle, pp.283-299.

Wadhams, P. and R.J. Home, 1980. An Analysis of Ice Profiles Obtained by Submarine Sonar in the Beaufort Sea. J. Glaciol. 25:401-424.

Walker, H.J., 1974. The Colville River and the Beaufort Sea: Some Interactions. Proceedings Symposium on Beaufort Sea Coast and Shelf Research, Arctic Institute of North America, December 1974.

Wang, Y.S., 1979. Sea Ice Properties. In: Technical Seminar on Alaskan Beaufort Sea Gravel Island, Exxon Co., USA, Houston.

Wang, J.L., V. Vivatrat and J.R. Rusher, 1982. Geotechnical Properties of Alaska OCS Silts. Proceedings Offshore Technology Conference (OTC Paper No. 4412), Houston, May 1982.

Wasilewski, B.R. and J.C. Bruce, 1981. Conceptual Design For A Mobile Arctic Gravity Platform. Proceedings Conference on Port and Ocean Engineering Under Arctic Conditions (POAC), Quebec, 1981.

Weeks, W.F., 1984. The Variation of Ice Strength Within and Between Multi-year Pressure Ridges in the Beaufort Sea. Proceedings Offshore Mechanics and Arctic Engineering Symposium, ASME, New Orleans, 1984.

Weeks, W.F. and S.F. Ackley, 1982. The Growth, Structure, and Properties of Sea Ice. CRREL Monograph 82-1, Hanover.

Weeks, W.F and A. Assur, 1967. The Mechanical Properties of Sea Ice. USA CRREL Cold Regions Science and Engineering IIC3.

Wetmore, S.B., 1984a. Concrete Island Drilling System Super Series (Super CIDS). Proceedings Symposium on Arctic Offshore Drilling Platforms, April 1984.

Wetmore, S.B., 1984b. Mobile Arctic Drilling Structure (MADS). Proceedings Symposium on Arctic Offshore Drilling Platforms, April 1984.

Wetmore, S.B. and J.S. Parsons, 1982. A Mobile Monopod Jackup Drilling System For Offshore Arctic Applications. Global Marine Development, Inc.

Wilson, S.G., 1977. Statistical Study of Passage into the Beaufort Sea Via Point Barrow. APOA Report No. 113, December 1977.

Wise, J.L. and A.L. Comiskey, 1980. Superstructure Icing in Alaskan Waters. Report prepared by the National Oceanic and Atmospheric Administration for the U.S. Department of Commerce.

Zubov, N.N., 1945. Arctic Ice. Izdatel'stvo Glavesmorputi, Moscow (in Russian).

# APPENDIX EVALUATION OF TYPICAL PETROLEUM DEVELOPMENT SCENARIOS

In order to illustrate the use of the information contained within this report, two typical petroleum development scenarios have been postulated and analyzed. While it is anticipated that TAPS will be available for production from the study area, the scenarios are based on the assumption that TAPS is not available so that the aspects of the transportation system selection process may be illustrated. Thus, the objectives of the analyses are to select the most cost. effective crude oil transportation system and then determine the total development project capital cost, annual operating cost and present value of the total capital and operating cost over the twenty-three year period from the decision to begin construction to the cessation of production. Each scenario has been analyzed separately assuming no linkage with each other nor with development elsewhere. except that a land pipeline paralleling the existing TAPS pipeline would utilize the existing haul road. It has been assumed that exploration and delineation well drilling has been completed and sufficient information regarding the reservoirs is available on which to base a decision to proceed with development. In addition, the analyses are based on the following assumptions:

- Environmental conditions will be as described in Section 3.1.
- Petroleum production parameters and well characteristics will be as described in Section 3.3.

- The scenarios are sufficiently remote from existing facilities to require an independent and complete base camp for exploration activities and this camp will be existing at the time a decision regarding production is to be made.
- An adequate dredge will be available and dredging costs will be as described in Section 4.1.2.
- Costs are based on delivering the crude oil to a trans-shipment terminal on the southern coast of the Alaska Peninsula or a terminal in the vicinity of Valdez. The cost of the terminals is not included.
- Permit requirements will not cause undue delays and permitting is not on the critical path to a field's development. (It is recognized that this may be an unrealistically optimistic assumption.)
- Sufficient engineering will be carried out prior to the decision to initiate development construction so that engineering will not be on the critical path.
- All costs are in constant January 1982 U.S. dollars and do not account for future inflation.
- All present value calculations are based on an 8 percent rate of return.
- The effects of taxes and royalties are not considered.
- Construction costs are considered to be expended uniformly over the construction period of each facility.

- A salvage value equal to the scrap value was assigned to vessels and all other facilities were assumed to have no salvage value.
- Post-production costs are not considered.

Of necessity, the two following illustrative examples are greatly simplified versions of the actual analyses that would be required in order for a decision regarding petroleum development to be made on a sound basis. Only the major parameters are considered in the examples and the analyses are based on simplification of the problems involved. For an actual development analysis, each of the many elements of the development scenario will require an engineering, environmental, economic and regulatory evaluation requiring far greater effort than has been allocated for this entire report.

The principal characteristics of the two scenarios considered are as follows:

| Characteristic | Scenario 1 | Scenario 2 |
|---|---|---|
| Scenario location | Western Region | Central Region |
| Production rate, BPD | 200,000 | 300,000 |
| Water depth, m (ft) | 80 (262) | 30 (98) |
| Distance from shore, km (mi) | 300 (186) | 50 (31) |
| Distance from marine pipeline landfall to TAPS, km (mi) | 600 (373 ) | 50 (31) |

| | | |
|---|---|---|
| Distance parallel with TAPS to Valdez, km (mi) | 1,200 (746) | 1,300 (808) |
| Length of icebreaker tanker route to transshipment terminal, km (mi) | 2,200 (1,370) | 2,700 (1,680) |

For each of the scenarios, costs were developed separately for pipeline and tanker crude oil transportation systems. The present value of the capital and operating cost over the twenty year life of the field were then compared.

## A.1 SCENARIO 1

Scenario 1 represents, for the base case production rate, a situation where the oil field is located close to the maximum distance from shore and in nearly the maximum water depth. The field is assumed to be developed by directional drilling from a single Conical Production Structure (CPS). Its location results in near the minimum icebreaker tanker travel distance for the tanker transportation alternative and near the maximum pipeline length for the pipeline alternative,

A simplified construction and development drilling schedule is shown in Figure A.1-1.

### A.1.1 Pipeline Transportation Alternative

(a-1) Marine Pipeline (Length = 300 km)

- Size

  From Figure 7.1-1: diameter = 26 in.

- Capital Cost

  From Figure 7.1-5: MM$630

- Annual Operating Cost

  From Figure 7.1-6: MM$22

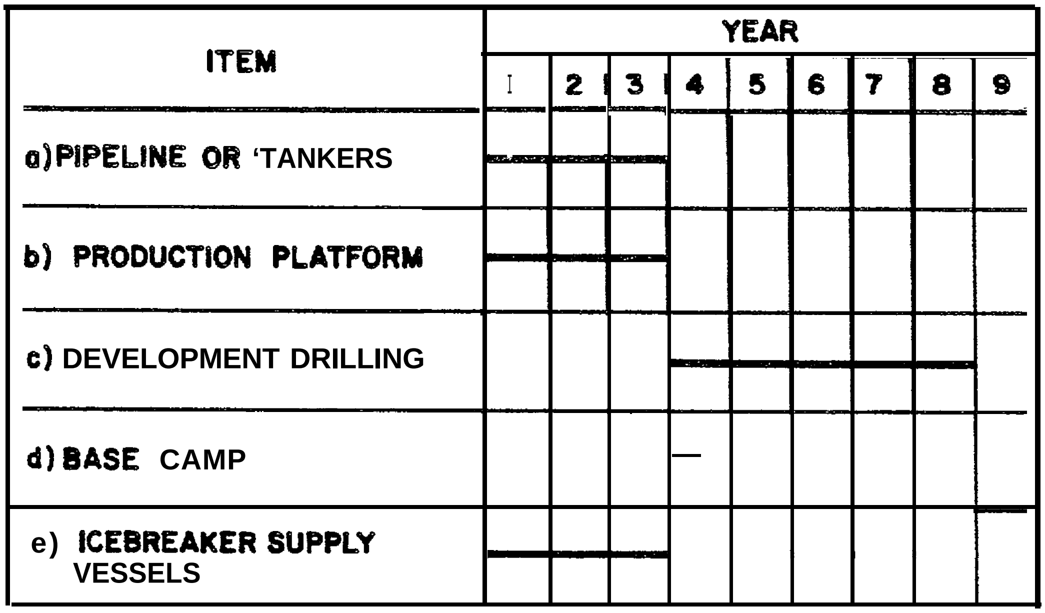

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Figure A. I-l. Scenario 1 construction and development drilling schedule.

## (a-2) Land Pipeline

- Length

  w/haul road = 600 km (Assume all above ground)

  w/o haul road = 1,200 km (Assume 50% buried)

- Size

  From Figure 7.2-1: diameter = 18 in.

- Capital Cost

  From Figure 7.2-2:

  600 km @ MM$2.1 = MM$1,260

  600 km @ MM$1.3 = MM$ 780

  600 km @ MM$1.9 = MM$1,140

  Total = MM$3,180

- Annual Operating Cost

  From Figure 7.2-2:

  600 km @ MM$.042 = MM$25

  600 km @ MM$.026 = MM$16

  600 km @ MM$.037 = MM$22

  Total = MM$63

(b) Production Platform

- Capital Cost

  From Figure 6.3-1: MM$784

- Annual Operating Cost

  From Section 4.2.2: MM$63 @ peak production

  From Section 6.3: MM$5

(c) Development Drilling

- Drilling Time (3,000 m deep wells)

  From Figure 4.3-3: 50 days per well per rig

  $\frac{360}{50}$ x 2 = 14 wells per year

- Drilling Cost

  From Figure 4.3-4: MM$5.1 per well

  14 X5.1 = MM$71 per year for the first four years of drilling.

  12 x 5.1 = MM$61 for the fifth year of drilling.

(d) Base Camp

- Capital Cost

  From Section 4.5.3: MM$50

- Annual Operating Cost

  From Section 4.5.3: MM$18 (assumed to decrease to MM$15 after development drilling is completed.

### (e) Sealift

- Tonnage

  Assume 2,500 tonnes of consumables per well.

  Assume 20,000 tonnes per year of miscellaneous consumables.

- Cost

  From Figure 4.4-1; $650 per tonne

  $650 x 2,500 = MM$1.6 per well

  $650 x 20,000 = MM$13 per year

### (f) Icebreaker Supply Vessels

- Number and Class

  From Table 4.4-2: 2 - Class 6

- Capital Cost

  From Figure 4.4-3: MM$100 each

- Operating Cost

  From Section 4.5.3 MM$5 each

### A.1.2 Tanker Transportation Alternative

#### (a) Tankers

- Size

From Section 7.5.1: Average speed

$> 4$ oktas = 6 knots = 11 km per hr

$< 4$ oktas = 20 knots = 37 km per hr

Assume 1,100 km $\geq$ 4 oktas

1,000 km $<$ 4 oktas

$$\text{Travel time} = \left(\frac{1100}{11} + \frac{1000}{37}\right)\frac{1}{24} = 5.3 \text{ days}$$

Port time = 2.0 days

Total Round Trip Time = 7.3 days

Assuming three tankers in service:

$$D = \frac{200{,}000 \times 7.3}{7.5 \times 0.95(3-1)} = 103{,}000 \text{ DWT}$$

- Capital Cost

From Figure 7.5-3; MM$225 each

- Annual Operating Cost

From Figure 7.5-3: MM$40 each when fully utilized

Assume 50 percent of operating cost is fixed and remainder is proportional to production rate.

(b) Production Platform

- Capital Cost

  From Figure 6.3-1: MM$784

  From Section 7.3.4: MM$100

  Total Capital Cost: = MM$884

- Annual Operating Cost

  From Section 4.2.2: MM$63 @ peak production

  From Section 6.3: MM$5

  From Section 7.3.4: MM$5

(c) through (e)

Same as (c) through (e) of Section A.1.1

(f) Icebreaker Supply Vessels

- Number and Class

  From Table 4.4-2: 2 - Class 8

- Capital Cost

  From Figure 4.4-3: MM$152 each

- Annual Operating Cost

  From Figure 4.4-3: MM$22 each

### A.1.3 Selection of Alternatives

Table Al-l presents a simplified analysis of the investment required to develop and produce the Scenario 1 oil field using the pipeline transportation alternative. Table A.1-2 is similar but for the tanker transportation alternative. A comparison of the total present value for each alternative makes it obvious that the tanker alternative is more cost effective.

## TABLE A.1-1

## SCENARIO 1: COST ANALYSIS - PIPELINE ALTERNATIVE

( ALL COST IN 1982 MM $ )

| ITEM | MILE-STONE | ◀ DECISION TO START CONSTR. | | | ◀ START DEVELOPMENT DRILLING | | | | | ◀ PEAK PRODUCTION REACHED | | | | | | | | | | | | | | | | | ◀ PRODUCTION CEASES |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | YEAR | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | SALVAGE |
| a) PIPELINE | | 1270 | 1270 | 1270 | 185 | 185 | 185 | 185 | 185 | 185 | 185 | 185 | 185 | 185 | 185 | 185 | 185 | 185 | 185 | 185 | 185 | 185 | 185 | 185 | |
| b) PRODUCTION PLATFORM | | 261 | 261 | 262 | 49 | 53 | 58 | 62 | 66 | 68 | 68 | 68 | 65 | 63 | 61 | 60 | 58 | 57 | 56 | 55 | 54 | 53 | 52 | 52 | |
| c) DEVELOPMENT | _ING | | | | 71 | 71 | 71 | 71 | 61 | | | | | | | | | | | | | | | | |
| d) BASE CAMP | | | | | 50 | 18 | 18 | 18 | 18 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | |
| e) SEALIFT | | | | | 35 | 35 | 35 | 35 | 32 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | |
| f) ICEBREAKER SUPPLY VESSELS | | 67 | 67 | 66 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | -20 |
| | | | | | | | | | | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | | | | | | | | | |
| TOTAL PER YEAR | | 1598 | 1598 | 1598 | 320 | 292 | 297 | 301 | 292 | 211 | 211 | 211 | 208 | 206 | 204 | 203 | 201 | 200 | 199 | 198 | 197 | 196 | 195 | 195 | -20 |
| PRESENT VALUE | | 1480 | 1370 | 1268 | 235 | 199 | 187 | 176 | 158 | 106 | 98 | 90 | 83 | 76 | 69 | 64 | 59 | 54 | 50 | 46 | 42 | 39 | 36 | 33 | -3 |
| | | | | | | | | | | | | | | | | | | | | | | | | | |

TOTAL PRESENT VALUE MM $ 6,015

## TABLE A.1-2

## SCENARIO 1: COST ANALYSIS - TANKER ALTERNATIVE

( ALL COST IN 1982 MM $ )

| ITEM | MILE-STONE | ◀ DECISION TO START CONSTR. | | | ● START DEVELOPMENT DRILLING | | | | | ◀ PEAK PRODUCTION REACHED | | | | | | | | | | | | | | | PRODUCTION CEASES |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | YEAR | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | SALVAGE |
| a) TANKERS | | 225 | 225 | 225 | 66 | 79 | 90 | 101 | 114 | 120 | 120 | 120 | 113 | 107 | 101 | 96 | 91 | 89 | 84 | 81 | 79 | 77 | 74 | 73 | -128 |
| b) PRODUCTION PLATFORM | | 295 | 295 | 294 | 54 | 58 | 63 | 67 | 71 | 73 | 73 | 73 | 70 | 68 | 66 | 65 | 63 | 62 | 61 | 60 | 59 | 50 | 57 | 57 | |
| c) DEVELOPMENT DRILLING | | | | | 71 | 71 | 71 | 71 | 61 | | | | | | | | | | | | | | | | |
| d) BASE CAMP | | | | | 50 | 18 | 18 | 18 | 18 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | |
| ● )SEALIFT | | | | | 35 | 35 | 35 | 35 | 32 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | |
| f) ICEBREAKER SUPPLY VESSELS | | 102 | 101 | 101 | 44 | 44 | 44 | 44 | 44 | 44 | 44 | 44 | 44 | 44 | 44 | 44 | 44 | 44 | 44 | 44 | 44 | 44 | 44 | 44 | -30 |
| | | | | | | | | | | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | | | | | | | | | |
| TOTAL PER YEAR | | 622 | 621 | 620 | 320 | 305 | 321 | 336 | 340 | 265 | 265 | 265 | 255 | 247 | 239 | 233 | 226 | 223 | 217 | 213 | 210 | 207 | 203 | 202 | -150 |
| PRESENT VALUE | | 576 | 532 | 494 | 235 | 208 | 202 | 196 | 184 | 133 | 123 | 114 | 101 | 91 | 81 | 73 | 66 | 60 | 54 | 49 | 45 | 41 | 37 | 34 | -27 |
| | | | | | | | | | | | | | | | | | | | | | | | | | |

TOTAL PRESENT VALUE MM $3,701

## A.2 SCENARIO 2

Scenario 2 represents, for the maximum production rate considered, a situation where the oil field is located close to shore and in nearly the minimum water depth. The field is assumed to be developed by directionally drilling a total of 68 production and injection wells from a central CPS platform and drilling a total of 34 production and injection wells at six satellite clusters with subsea completions and flowlines to the main platform. The satellite wells are drilled from a CDS type drilling platform, relocated each summer over a six year period. The location of the scenario results in near the minimum pipeline length for the pipeline transportation alternative and a quite long icebreaker tanker travel distance for the tanker transportation alternative.

A simplified construction and development drilling schedule is shown in Figure A.2-1.

### A.2.1 Pipeline Transportation Alternative

(a-1 ) Marine Pipeline (Length = 50 km)

- Size

  From Figure 7.1-1: diameter = 24 in.

- Capital Cost

  From Figure 7.1-5: MM$210

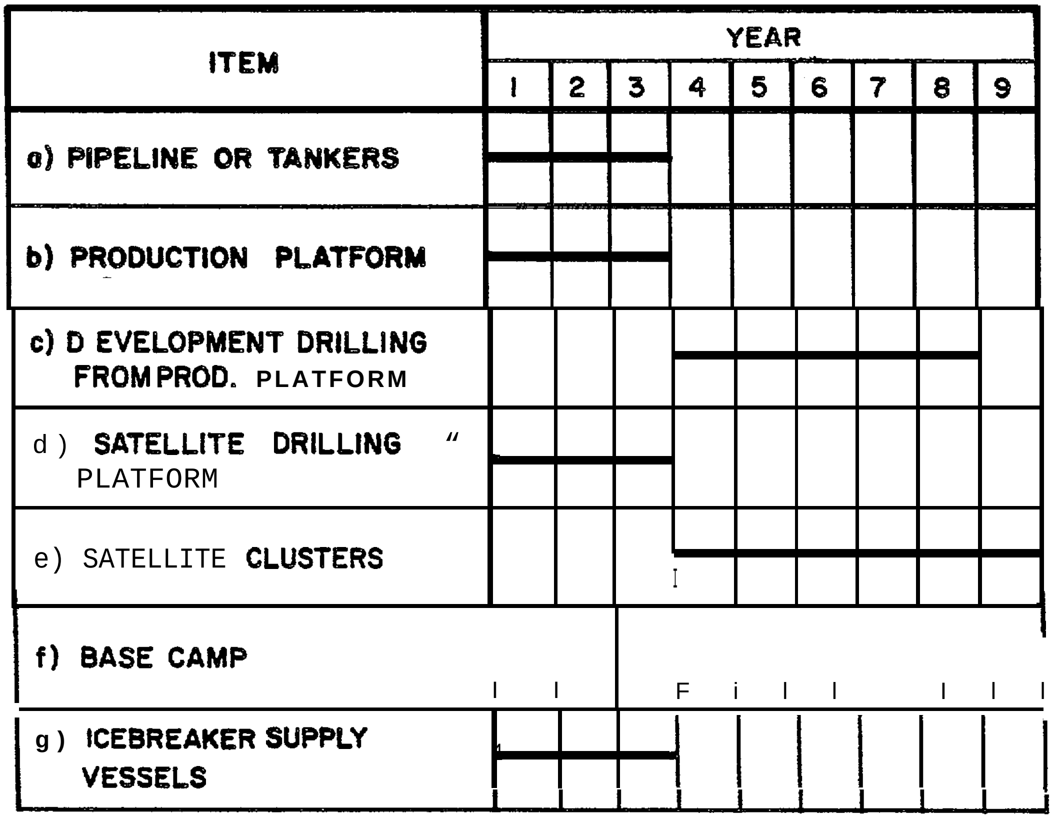

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Figure A.2-1. Scenario 2 construction and development drilling schedule.

- Annual Operating Cost

  From Figure 7.1-6: MM$7

## (a-2) Land Pipeline

- Length

  w/haul road = 50 km (Assume all above ground)

  w/o haul road = 1,300 km (Assume 50% buried)

- Size

  From Figure 7.2-1: diameter = 20 in.

- Capital Cost

  From Figure 7.2-2:

| | |
|---|---|
| 50 km @ MM$2.2 = | MM$ 110 |
| 650 km @ MM$1.9 = | MM$1,235 |
| 650 km @ MM$1.3 = | MM$ 845 |
| Total = | MM$2,190 |

- Annual Operating Cost

  From Figure 7.2-2:

| | |
|---|---|
| 50 km @ MM$.045 = | MM$ 2 |
| 650 km @ MM$.039 = | MM$25 |
| 650 km @ MM$.027 = | MM$18 |
| Total = | MM$45 |

(b) Production Platform

- Capital Cost

  From Figure 6.3-1: MM$810

e Annual Operating Cost

  From Section 4.2.2: MM$69 @ peak production

  From Section 6.3: MM$5

(c) Development Drilling from Production Platform

- Drilling Time (3,000 m deep wells) "

  From Figure 4.3-3: 50 days per well per rig

  $\frac{360}{50} \times 2 =$ 14 wells per year

- Drilling Cost

  From Figure 4.3-4: MM$5.1 per well

  14 x 5.1 = MM$71 per year for the first four years of drilling.

  12 x 5.1 = MM$61 for the fifth year of drilling.

(d) Satellite Drilling Platform

- Structure Capital Cost

  From Figure 5.2-9: MM$160

- Topsides Capital Cost

  From Table 4.2-1: MM$33

- Total Capital Cost

  160 + 33 = MM$193

- Annual Operating Cost

  From Section 5.2.2: MM$3

- Annual Relocation Cost

  Allow MM$20

(e) Satellite Clusters (Costs indicated are for one six-well cluster. Six clusters are required.)

- Drilling Cost

  From Figure 4.3-4: MM$5.1 per well

  6 X 5.1 = MM$31

- Dredging 150 m dia x 8 m deep Glory Hole

  From Figure 4.1-5: dredging = $19 per $m^3$

  250,000 $m^3$ x 19 = MM$5

- Template, Completion and FlowTines

  Allow MM$50

- Total Capital Cost for Each Cluster

  31 + 5 + 50 = MM$86

- Total Annual Cost for Each Cluster

  Allow MM$5

(f) Base Camp

- Capital Cost

  From Section 4.5.3: MM$50

- Annual Operating Cost

  From Section 4.5.3: MM$18 (assumed to decrease to MM$15 after development drilling is completed. )

(g) Sealift

- Tonnage

  Assume 2,500 tonnes of consumables per well.

  Assume 20,000 tonnes per year of miscellaneous consumables.

- cost

  From Figure 4.4-1; $650 per tonne

  $650 x 2,500 = MM$1.6 per well

  $650 x 20,000 = MM$13 per year

### (h) Icebreaker Supply Vessels

- Number and Class

  From Table 4.4-2: 2 - Class 6

- Capital Cost

  From Figure 4.4-3: MM$100 each

- Operating Cost

  From Figure 4.4-3: MM$15 each

## A.2.2 Tanker Transportation Alternative

### (a) Tankers

- Size

  From Section 7.5.1: Average speed

  $\geq$ 4 oktas = 6 knots = 11 km per hr

  < 4 oktas = 20 knots = 37 km per hr

  Assume 1,700 km $\geq$ 4 oktas

  1,000 km < 4 oktas

  $$\text{Travel time} = \left( \frac{1700}{11} + \frac{1000}{37} \right) \frac{1}{24} = 7.6 \text{ days}$$

  Port time = 2.0 days

  Total Round Trip Time = 9.6 days

Assuming three tankers in service:

$$D = \frac{200,000 \times 9.6}{7.5 \times 0.95(3-1)} = 135,000 \text{ DWT}$$

- Capital Cost

  From Figure 7.5-3; MM$255 each

- Annual Operating Cost

  From Figure 7.5-3: MM$43 each when fully utilized

  Assume 50 percent of operating cost is fixedand remainder is proportional to production rate.

(b)- Production Platform

- Capital Cost

  From Figure 6.3-1: MM$810

  From Section 7.3.4: MM$100

  Total Capital Cost: =MM$910

- Annual Operating Cost

  From Section 4.2.2: MM$69 @ peak production

  From Section 6.3: MM$5

  From Section 7.3.4: MM$5

(c) through (g)

Same as (c) through (g) of Section A.2.1

(h) Icebreaker Supply Vessels

- Number and Class

  From Table 4.4-2: 2 - Class 8

- Capital Cost

  From Figure 4.4-3: MM$152 each

- Annual Operating Cost

  From Figure 4.4-3: MM$22 each

### A.2.3 Selection of Alternatives

Table A.2-1 presents a simplified analysis of the Investment required to develop and produce the Scenario 2 oil field using the pipeline transportation alternative. Table A.2-2 is similar but for the tanker transportation alternative. A comparison of the total present value for each alternative makes it obvious that the tanker alternative is more cost effective.

## TABLE A.2-1
## SCENARIO 2: COST ANALYSIS - PIPELINE ALTERNATIVE
( ALL COST IN 1982 MM $ )

| ITEM | MILE-STONE | ◀ DECISION TO START CONSTR. | | | ◀ START DEVELOPMENT DRILLING | | | | | | PEAK PRODUCTION REACHED | | | | | | | | | | | | | | ◀ PRODUCTION CEASES |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | YEAR | 1 | 2 | 3 | 4 | 5 | 6 | ? | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | SALVAGE |
| a) PIPELINE | | 800 | 800 | 800 | 52 | 52 | 52 | 52 | 52 | 52 | 52 | 52 | 52 | 52 | 52 | 52 | 52 | 52 | 52 | 52 | 52 | 52 | 52 | 52 | |
| b) PRODUCTION PLATFORM | | 270 | 270 | 270 | 53 | 58 | 63 | 67 | 72 | 74 | 74 | 74 | 71 | 69 | 67 | 65 | 63 | 62 | 60 | 59 | 58 | 57 | 57 | 56 | |
| c) PRODUCTION PLATFORM DEVELOPMENT DRILLING | | | | | 71 | 71 | 71 | 71 | 61 | | | | | | | | | | | | | | | | |
| d) SATELLITE WILLING PLATFORM | | 65 | 64 | 64 | 23 | 23 | 23 | 23 | 23 | 23 | | | | | | | | | | | | | | | |
| ,) SATELLITE CLUSTERS | | | | | 86 | 91 | 96 | 101 | 106 | 111 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | |
| f) BASE CAMP | | | | | 50 | 18 | 18 | 18 | 18 | 18 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | |
| g) SEALIFT | | | | | 45 | 45 | 45 | 45 | 42 | 19 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | |
| h) ICEBREAKER SUPPLY VESSELS | | 66 | 67 | 67 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | -20 |
| TOTAL PER YEAR | | 1201 | 1201 | 1201 | 410 | 388 | 398 | 407 | 404 | 327 | 214 | 214 | 214 | 209 | 207 | 205 | 203 | 202 | 200 | 199 | 198 | 197 | 197 | 196 | -20 |
| PRESENT VALUE | | 1112 | 1030 | 953 | 301 | 264 | 251 | 237 | 218 | 164 | 99 | 92 | 85 | 77 | 70 | 66 | 59 | 55 | 50 | 46 | 42 | 39 | 36 | 33 | - 3 |
| | | | | | | | | | | | | | | | | | | | | | | | | | |

TOTAL PRESENT VALUE MM $5,376

## TABLE A.2-2

## SCENARIO 2: COST ANALYSIS - TANKER ALTERNATIVE

( ALL COST IN 1982 MM $ )

| ITEM | MILE-STONE | ◀ DECISION TO START CONSTR. | | | ◀ START DEVELOPMENT DRILLING | | | | | | ◀ PEAK PRODUCTION REACHED | | | | | | | | | | | | | | ◀ PRODUCTION CEASES |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | YEAR | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | SALVAGE |
| a) TANKERS | | 255 | 255 | 255 | 71 | 54 | 97 | 110 | 122 | 129 | 129 | 129 | 121 | 114 | 108 | 103 | 99 | 95 | 91 | 88 | 85 | 82 | '$0 | 78 | -77 |
| b) PRODUCTION PLATFORM | | 303 | 303 | 304 | 58 | 63 | 68 | 72 | 77 | 79 | 79 | 79 | 76 | 74 | 72 | 70 | 68 | 67 | 66 | 64 | 63 | 62 | 61 | 61 | |
| c) PRODUCTION PLATFORM DEVELOPMENT DRILLING | | | | | 71 | 71 | 71 | 71 | 61 | | | | | | | | | | | | | | | | |
| d) SATELLITE DRILLING PLATFORM | | 64 | 66 | 64 | 23 | 23 | 23 | 23 | 23 | 23 | | | | | | | | | | | | | | | |
| e) SATELLITE CLUSTERS | | | | | 86 | 91 | 96 | 101 | 106 | 111 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | |
| f) BASE CAMP | | | | | 50 | 18 | 18 | 18 | 18 | 18 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | |
| g) SEALIFT | | | | | 45 | 45 | 45 | 45 | 42 | 19 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | |
| h) ICEBREAKER SUPPLY VESSELS | | 102 | 101 | 101 | 44 | 44 | 44 | 44 | 44 | 44 | 44 | 44 | 44 | 44 | 44 | 44 | 44 | 44 | 44 | 44 | 44 | 44 | 44 | 44 | -30 |
| TOTAL PER YEAR | | 724 | 724 | 724 | 448 | 439 | 462 | 464 | 493 | 423 | 310 | 310 | 299 | 290 | 282 | 275 | 269 | 264 | 259 | 254 | 250 | 246 | 243 | 241 | -107 |
| PRESENT VALUE | | 670 | 621 | 575 | 329 | 299 | 291 | 282 | ,266 | 212 | 144 | 133 | 119 | 107 | 96 | 87 | 78 | 7s | 65 | 59 | 54 | 49 | 45 | 41 | -18 |

TOTAL PRESENT VALUE MM $0,675