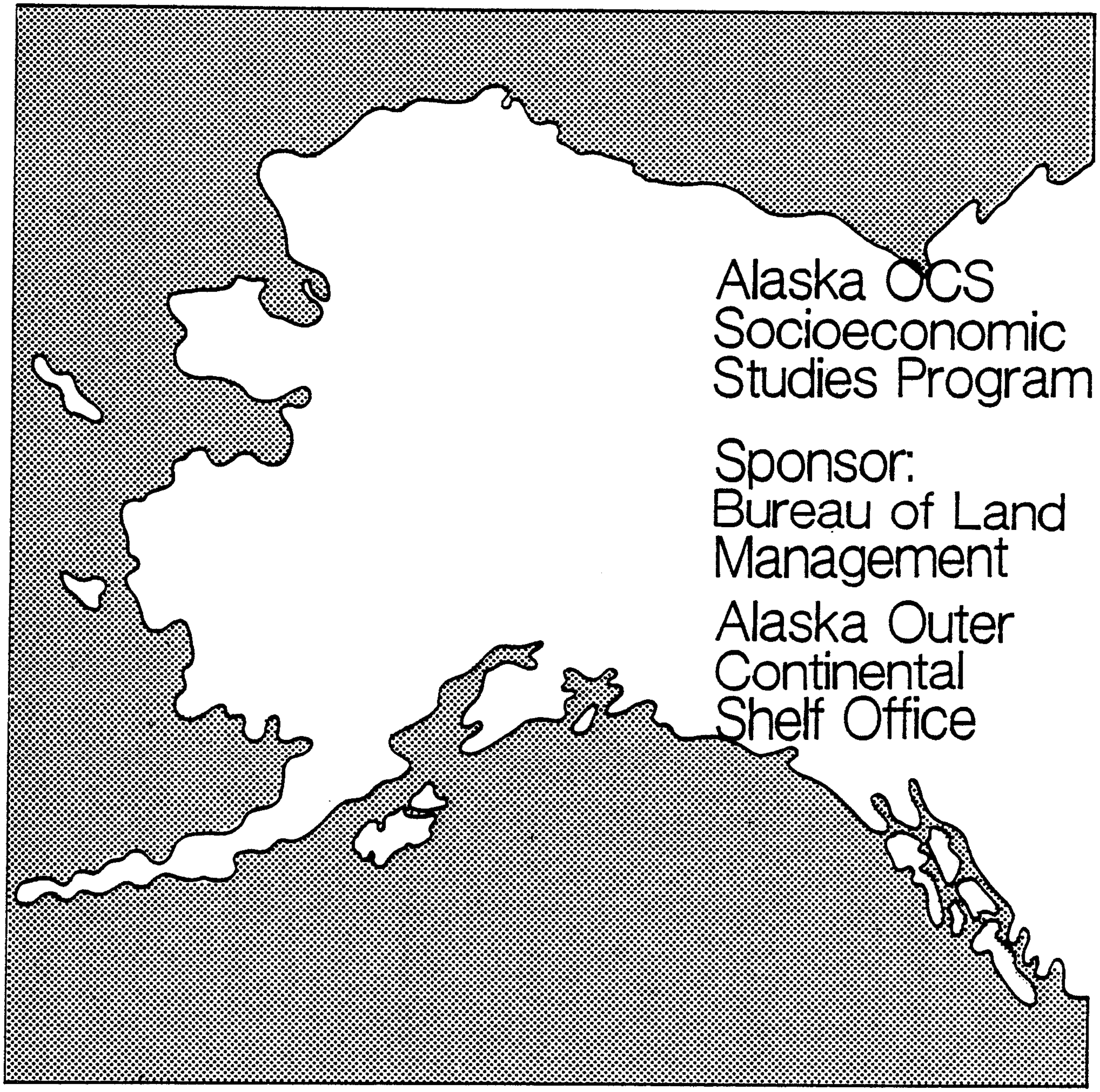
AUG 25 1983

Technical Report Number 79



Alaska OCS Socioeconomic Studies Program

Sponsor: Bureau of Land Management Alaska Outer Continental Shelf Office

Chukchi Sea Petroleum Technology Assessment

The United States Department of the Interior was designated by the Outer Continental Shelf (OCS) Lands Act of 1953 to carry out the majority of the Act's provisions for administering the mineral leasing and development of offshore areas of the United States under federal jurisdiction. Within the Department, the Bureau of Land Management (BLM) has the responsibility to meet requirements of the National Environmental Policy Act of 1969 (NEPA) as well as other legislation and regulations dealing with the effects of offshore development. In Alaska, unique cultural differences and climatic conditions create a need for developing additional socioeconomic and environmental information to improve OCS decision making at all governmental levels. In fulfillment of its federal responsibilities and with an awareness of these additional information needs, the BLM has initiated several investigative programs, one of which is the Alaska OCS Socioeconomic Studies Program (SESP).

The Alaska OCS Socioeconomic Studies Program is a multi-year research effort which attempts to predict and evaluate the effects of Alaska OCS Petroleum Development upon the physical, social, and economic environments within the state. The overall methodology is divided into three broad research components. The first component identifies an alternative set of assumptions regarding the location, the nature, and the timing of future petroleum events and related activities. In this component, the program takes into account the particular needs of the petroleum industry and projects the human, technological, economic, and environmental offshore and onshore development requirements of the regional petroleum industry.

The second component focuses on data gathering that identifies those quantifiable and qualifiable facts by which OCS-induced changes can be assessed. The critical community and regional components are identified and evaluated. Current endogenous and exogenous sources of change and functional organization among different sectors of community and regional life are analyzed. Susceptible community relationships, values, activities, and processes also are included.

The third research component focuses on an evaluation of the changes that could occur due to the potential oil and gas development. Impact evaluation concentrates on an analysis of the impacts at the statewide, regional, and local level.

In general, program products are sequentially arranged in accordance with BLM's proposed OCS lease sale schedule, so that information is timely to decisionmaking. Reports are available through the National Technical Information Service, and the BLM has a limited number of copies available through the Alaska OCS Office. Inquiries for information should be directed to: Program Coordinator (COAR), Socioeconomic Studies Program, Alaska OCS Office, P. O. Box 1159, Anchorage, Alaska 99510.

Technical Report

ALASKA OCS SOCIOECONOMIC STUDIES PROGRAM
BARROW ARCH PLANNING AREA
(CHUKCHI SEA)
PETROLEUM TECHNOLOGY ASSESSMENT
OCS LEASE SALE NO. 85

Prepared for

MINERALS MANAGEMENT SERVICE
ALASKA OUTER CONTINENTAL SHELF OFFICE

by

Jerry C. Wilson
William W. Wade
M.L. Feldman
D.R. Younger

of

DAMES & MOORE

in association with
SF/Braun
Thomas R. Marshall, Jr.
Brian Watt Associates, Inc.
Gordon S. Harrison
Ogden Beeman and Associates

DECEMBER 1982

Contract No. AA851-CT1-37

Job No. 08699-026-20

TABLE OF CONTENTS

		Page
1.0	INTRODUCTION	1-1
1.1	Purposes	1-1
1.2	Background and Scope	1-1
1.3	Data Gaps and Limitations	1-5
1.4	Report Content and Format	1-6
2.0	SUMMARY OF FINDINGS	2-1
2.1	Petroleum Geology	2-1
2.2	Environmental Constraints	2-3
2.3	Petroleum Technologies and Production Strategies	2-4
2.4	Manpower	2-6
2.5	Economics of Oil and Gas Development	2-7
3.0	RESULTS OF THE PETROLEUM TECHNOLOGY ASSESSMENT	3-1
3.1	Introduction	3-1
3.2	Environmental Constraints to Petroleum Development	3-2
3.2.1	Meteorology and Geography	3-2
3.2.1.1	Meteorology	3-2
3.2.1.2	Bathymetry	3-8
3.2.1.3	Circulation	3-10
3.2.1.4	Tides and Storm Surges	3-14
3.2.1.5	Waves	3-16
3.2.1.6	Sea Ice	3-18
3.2.2	Geology and Geologic Hazards	3-33
3.2.2.1	Major Data Sources and Reference Materials	3-33
3.2.2.2	Geologic Setting	3-33
3.2.2.3	Geologic Hazards	3-36
3.2.3	Biology	3-41

TABLE OF CONTENTS
(Continued)

Page

3.3 Field Development Components 3-43

3.3.1 Exploration Platforms and Operations 3-45

3.3.1.1 Exploration Platforms Selected for Representative Water Depths 3-47
3.3.1.2 Construction, Transportation and Installation Techniques for Selected Exploration Concepts 3-49

3.3.2 Production Platforms 3-70
3.3.2.1 Background 3-70
3.3.2.2 Platforms for the Barrow Arch Planning Area 3-72
3.3.2.3 Well Slot Limitations 3-77
3.3.2.4 Platform Construction, Transportation, and Installation Techniques 3-77

3.3.3 Wells 3-89
3.3.4 Pipelines 3-91
3.3.5 Offshore Loading and Storage 3-95
3.3.6 Subsea Completions 3-99
3.3.7 Arctic Early Production Systems 3-103
3.3.8 Marginal Field Development 3-103
3.3.9 Alternative Dredging Approach for Island Construction in the Chukchi Sea 3-105

3.4 Production Conditions and Field Development Strategies for the Barrow Arch Planning Area 3-107

3.4.1 Field Size 3-108
3.4.2 Reservoir and Production Characteristics 3-108
3.4.3 Quality and Physical Properties of Oil and Gas 3-108
3.4.4 Distance to Shore 3-110
3.4.5 Meteorological and Environmental Conditions 3-111
3.4.6 Location of Terminals 3-112
3.4.7 Barrow Arch Production Strategies Selected for Economic Analysis -- Summary 3-113

4.0 PETROLEUM FACILITIES ONSHORE SITING 4-1

4.1 Overview of Onshore Facilities 4-1

4.2 Physical Environment of the Region 4-2

TABLE OF CONTENTS
(Continued)

Page

4.2.1 Sand and Gravel Resources 4-3
4.2.2 Freshwater Sources 4-3

4.3 Types of Onshore Facilities Required 4-3

4.3.1 Marine Service Bases 4-6
4.3.1.1 Exploration-Related Facilities 4-7
4.3.1.2 Production-Related Facilities 4-10
4.3.2 Marine Terminal 4-12
4.3.3 Pipeline Service Requirements 4-14
4.3.4 Natural Gas Liquefaction Plants and Terminals 4-14
4.3.5 Summary of Petroleum Facility Siting Requirements . . 4-14

4.4 Onshore Facilities Siting Constraints and Criteria 4-14

4.5 Socioeconomic Setting and Regulatory Constraints 4-18

4.6 Representative Onshore Facility Sites in the Barrow Arch Planning Area 4-19

5.0 MANPOWER REQUIREMENTS 5-1

5.1 Introduction 5-1

5.2 General: Three Phases of Petroleum Resource Labor Activities 5-1

5.3 Background: Manpower Utilization in an Arctic Environment 5-9

5.3.1 Expense of Labor in the Arctic 5-9
5.3.2 Labor Saving Techniques 5-10
5.3.3 Prefabricated, Barge-Mounted LNG Plant 5-11
5.3.4 Labor Intensive Arctic Construction 5-13
5.3.5 Construction of Artificial Islands 5-14
5.3.6 Additional Factors Effecting Labor Utilization 5-14

5.4 Barrow Arch Labor Force Considerations 5-15

5.4.1 Longer Crew Rotations 5-15
5.4.2 Major Shore Facilities Required 5-16
5.4.3 Offshore Construction 5-17

TABLE OF CONTENTS
(Continued)

Page

6.0 THE ECONOMICS OF PETROLEUM DEVELOPMENT 6-1

6.1 Introduction and Modeling Approach 6-1

6.2 Development Scenarios Used for Economic Analysis 6-3

6.2.1 Comparison of Five Scenarios 6-3
6.2.2 Analytical Assumptions for Oil Reservoirs 6-5
6.2.3 Descriptions of Scenarios 6-9

6.3 Results of the Economic Analysis 6-16

6.3.1 Economic Comparison of Alternative Offshore Production Systems 6-18
6.3.2 Economic Comparison of Alternative Transportation Systems 6-20
6.3.3 Economic Comparison of Alternative Field Sizes 6-21
6.3.4 Price Sensitivity of the Analysis 6-22

6.4 Equivalent Amortized Costs of Oil Development 6-22

6.5 Conclusions Regarding the Economic Viability of Developing Barrow Arch Area Oil Resources 6-24

6.6 Development of Barrow Arch Area Gas Resources 6-26

6.6.1 Gas Development Considerations 6-26
6.6.2 Description of Non-Associated Gas Development Scenarios 6-27
6.6.3 Economic Results of Barrow Arch Area Gas Field Development Scenarios 6-29
6.6.4 Economics of Associated Gas from Barrow Arch Area . . 6-32

6.7 Relationship of Barrow Arch Area Oil Production to the U.S. Energy Balance 6-34

6.7.1 Consensus Energy Forecasts 6-34
6.7.2 Oil Price Growth through 2000 6-37
6.7.3 The Relationship of Barrow Arch Planning Area Production to PAD V Supply and Demand 6-40
6.7.3.1 PAD V Supply/Demand Balance: 1978-1981 6-40
6.7.3.2 PAD V Petroleum Product Demand Forecast: 1990 6-42
6.7.3.3 West Coast Supply/Demand Forecast with Reference to Barrow Arch Planning Area 6-44

TABLE OF CONTENTS
(Continued)

Page

7.0 HYPOTHETICAL PETROLEUM SCENARIOS FOR THE ESTIMATED MEAN OIL AND GAS RESOURCES OF THE CENTRAL CHUKCHI SHELF 7-1

7.1 Introduction 7-1

7.2 Development Strategy and Production Facilities 7-1

8.0 BIBLIOGRAPHY

APPENDIX A

APPENDIX B

LIST OF TABLES

Table		Page
3-1	Air Temperatures at Arctic Coastal Stations	3-4
3-2	Precipitation at Arctic Coastal Stations	3-6
3-3	Surface Winds at Arctic Coastal Stations	3-7
3-4	Fog Conditions at Arctic Coastal Stations	3-9
3-5	Seasonal Wave Activity for Barrow Arch Planning Area Percent Frequency of Observed Wave Height Thresholds (Non-Hazardous Sea Conditions) in Chukchi Sea (North of 70° N Latitude)	3-19
3-6	Extrapolated Pressure Ridge Characteristics and Frequency	3-26
3-7	Generalized Ice Loads for Representative Drilling Structures in Deeper Water	3-32
3-8	Equipment Spread for Construction of a Gravel Island in 15 Meter (50 Foot) Water Depth	3-52
3-9	Island Fill Requirements	3-58
4-1	Summary of Petroleum Facility Siting Requirements	4-16
5-1	Estimates of Labor Requirements for Specific Tasks of Petroleum Development in the Barrow Arch Planning Area	5-2
5-2	Estimates of Helicopter and Support Vessel Units and Crews for Offshore Activity in the Barrow Arch Planning Area	5-5
6-1	Equipment and Capital Investments for Barrow Arch Oil Development	6-6
6-2	Results of Economic Analysis of Barrow Arch Area Petroleum Development	6-17
6-3	Equivalent Amortized Costs of Selected Barrow Arch Area Oil Development Scenarios	6-23
6-4	Results of Economic Analysis for Barrow Arch Area Gas Field Development	6-30
6-5	Equivalent Amortized Costs of Barrow Arch Area Gas Field Development Scenarios	6-33

LIST OF TABLES
(Continued)

Table		Page
6-6	U.S. Energy Forecasts	6-36
6-7	Arab Light Crude Oil Price Forecasts -- Annual Real Rate of Growth	6-38
6-8	U.S. District V Supply/Demand Balance: 1978-1981	6-41
6-9	Pad V 1990 Product Demand Forecast	6-43
6-10	Impact of Potential Barrow Arch Area Production on Pad V. . .	6-45
6-11	California Crude Oil Production Forecast	6-47
7-1	Central Chukchi Shelf Hypothetical Petroleum Development Case	7-2

LIST OF FIGURES

Figure		Page
1-1	General Location Map of Proposed Barrow Arch OCS Lease Sale No. 85 in the Northeast Chukchi Sea	1-3
2-1	Arctic Offshore Oil & Gas Provinces	2-2
3-1	Bathymetry in the Northeast Chukchi Sea	3-11
3-2	Surface Currents in the Northeast Chukchi Sea	3-13
3-3	Alaskan Arctic Seas & Extent of Sea Ice	3-20
3-4	Spring Ice Zonation of the Alaska Beaufort Sea	3-22
3-5	Late Winter Ice Zonation of the Alaska Beaufort Sea	3-23
3-6	Interaction of a Floating Ice Beam with an Inclined Structure	3-32
3-7	Distribution of Bottom Sediments, Chukchi Sea	3-35
3-8	Distribution of Ice Gouges, Offshore Alaska	3-37
3-9	Elevation of Arctic Exploratory Drilling Island	3-53
3-10	General Design of Shore Protection for Artificial Islands . .	3-56
3-11	Caisson Retained Island	3-59
3-12	Caisson Retained Island Simplified General Arrangement . . .	3-60
3-13	Caisson Retained Island Rhombic Configuration During Transportation	3-61
3-14	Gulf Canada Beaufort Sea Mobile Arctic Caisson	3-65
3-15	Gulf Canada Beaufort Sea Drilling Barge	3-68
3-16	Mobile Arctic Drill Barge Concept	3-71
3-17	Arctic Drilling & Expanded Production Island	3-79
3-18	ESSO Resources Arctic Monocone	3-81
3-19	Dome Petroleum Arctic Monocone & Its Towing & Installation. .	3-83
3-20	Dome Petroleum Artificial Production & Loading Atoll (APLA)	3-85

LIST OF FIGURES
(Continued)

Figure		Page
3-21	Dome Petroleum Arctic Super Dredge	3-87
3-22	Directional Drilling Chart	3-90
3-23	Typical Permafrost Casing Program	3-92
3-24	Arctic Floating Caisson	3-96
3-25	Subsea Tree With Through Flow Line (TFL) Control	3-102
4-1	Distribution of Surficial Gravel Deposits	4-4
4-2	Bottom Sediment Types	4-5
4-3	Crude Oil Marine Terminal	4-13
4-4	Liquefaction Plant & LNG Marine Terminal	4-15
4-5	Representative Oil & Gas Development Onshore Facilities . . .	4-17
4-6	Representative Field & Shore Facility Locations - Northern Portion	4-22
4-7	Representative Field & Shore Facility Locations - Southern Portion	4-23
5-1	Local Employment Created by the Three Phases of Petroleum Exploration, a Hypothetical Case	5-8
6-1	West Coast/Demand Forecast	6-46
A-1	Preliminary Tectonic Map of Chukchi Shelf & Petroleum Geology Study Areas	A-8

1.0 INTRODUCTION

1.1 Purposes

The principal purpose of this study is to identify the petroleum technology that may be used to develop oil and gas resources for the Barrow Arch OCS Lease Sale No. 85. This analysis focuses on both the individual field development components (types of platforms, pipelines, etc.) and the overall field development and transportation strategies. An evaluation of the environmental constraints (oceanography, geology, etc.) defines the most suitable engineering strategies.

The second purpose of this study is to assess the economic viability of various development strategies. In view of the severe ice conditions, harsh environment and remote location of the Barrow Arch planning area, the economic analysis has focused on the economic viability of different combinations of exploration and production concepts along with various transportation alternatives. The third purpose is to estimate the manpower required to construct and operate the facilities selected for analysis.

1.2 Background and Scope

This petroleum technology assessment is for the Barrow Arch Lease Sale No. 85. Scheduled for February 1985, it will be the first lease sale in the Barrow Arch planning area, one of three arctic planning areas. It will be preceded by two sales in the Diapir Field arctic planning area, Diapir Field Lease Sale No. 71 and Diapir Field Lease Sale No. 87 (scheduled for September 1982 and June 1984, respectively). A proposed lease sale for the third arctic planning area, the Hope Basin, was recently deleted from the 5-year OCS oil and gas leasing schedule. Barrow Arch planning area, the subject of this report, was formerly called the Chukchi Sea planning area until its boundaries were modified to better represent underlying geologic structures. It was reduced in size so that certain geologic formations could be consolidated into the Diapir Field, formerly called the Beaufort Sea planning area. The present Barrow Arch planning area encompasses the area shown in Figure 1-1, which is bounded on the north by 73°N latitude, on the east by the 162°W meridian running south to 71°N latitude where the boundary runs eastward until it reaches the 3-mile limit of Alaska waters; it is roughly bounded on the south by a line westward from Point Hope (about 68° 15'N latitude) and to the west by the U.S.-Russia Convention Line of 1867 (about 169° W longitude).

This study is structured to provide "building blocks" of the petroleum facilities, equipment, costs, and employment that can be used by Minerals Management Service Alaska OCS Region staff to evaluate nominated lease tracts. Six scenarios involving a total of 12 feasible field development strategies for oil and gas (types of platforms, transportation options, etc.) were examined; all of these development strategies, while technically feasible, are uneconomic to marginally sub-economic under the assumptions given.

Petroleum technology, in conjunction with the regulatory framework and any stipulations, will influence or determine the scheduling of offshore and onshore activities, the local employment and infrastructure support requirements, and the potential risks involved in the production and transportation of hydrocarbons and related potential for environmental impacts. Thus, this petroleum technology assessment provides a key part of the necessary framework to assess the environmental and socioeconomic impacts of petroleum development in the Barrow Arch planning area.

This report provides early information for the Minerals Management Service to initiate planning for the lease sale. As such, this is part of the regulatory process for OCS development, but specific stipulations regarding this lease sale are not known at this time. Therefore, our scheduling assumptions for development scenarios (specifically Sections 6.2.3 and 7.2) make only a general allowance for the permit process. We make the optimistic assumption that permits are not the critical path to a field's development (see discussion in Section 6.3). It is basically assumed that permits can be successfully obtained simultaneous with other early development steps. This is feasible to a point (Pritchard 1982), but

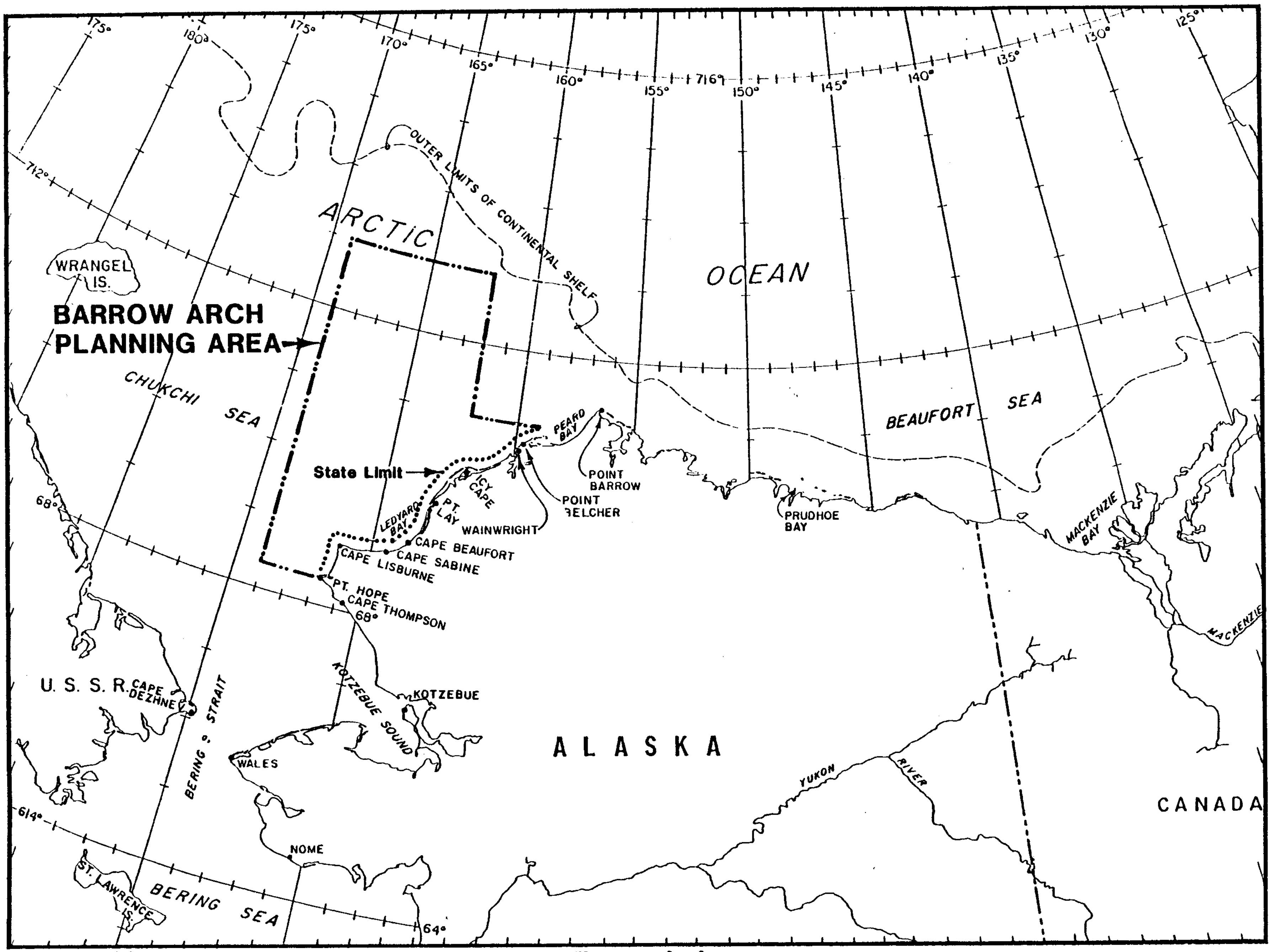


Figure 1-1
GENERAL LOCATION MAP
OF PROPOSED BARROW ARCH OCS LEASE SALE NO. 85 IN THE NORTHEAST CHUKCHI SEA

the ultimate commitment of the decision to develop is significantly affected by permitting requirements.

It should be emphasized that this report is specifically designed to provide petroleum development data for the Alaska OCS socioeconomic studies program. This study, along with other studies conducted by or for the Minerals Management Service, including environmental impact statements, is required to use U.S. Geological Survey estimates of recoverable oil and gas. However, at the time this report was prepared, no U.S. Geological Survey resources report was available specifically for the Barrow Arch planning area. Therefore, estimates of recoverable oil and gas were obtained from the recent National Petroleum Council's report on U.S. Arctic Oil and Gas (1981) and an independent evaluation of the area's petroleum geology (Appendix A). Therefore, the assumptions used in the analysis may be subject to revision as new data become available.

The principal components of this study are:

- An evaluation of the environmental constraints (oceanography, geology) that will influence or determine petroleum engineering field development and transportation strategies (Chapter 3.0).

- A review of state-of-the-art and conceptual technology for exploration, production and transportation of oil and gas from arctic regions (Chapter 3.0).

- A description of various field development components, strategies and related technical problems (Chapter 3.0).

- A discussion of facilities siting to identify suitable shore sites for petroleum facilities such as crude oil terminals, LNG plants and support bases (Chapter 4.0).

- An analysis of the manpower requirements to explore, develop, and produce Barrow Arch petroleum resources in the context of projected technology, and environmental and logistical constraints. This includes specification of manpower requirements by individual tasks and facilities. (Chapter 5.0).

- A review of the petroleum geology of the Barrow Arch planning area to formulate reservoir and production assumptions necessary for the economic analysis (Appendix A).

- An economic analysis of Barrow Arch petroleum resources in the context of projected technology, facility and equipment costs, and assumed reservoir characteristics (Chapter 6.0).

- Specification of the facility, equipment requirements and probable production for a hypothetical development case corresponding to the National Petroleum Council's statistical mean oil and gas resource estimate for the basin's central Chukchi shelf (Chapter 7.0).

1.3 Data Gaps and Limitations

Results of this study are preliminary and should be reviewed in the context of the constraints imposed on the analysis by significant data gaps. This study is based upon available data such as the geophysical records of the U.S. Geological Survey and the results of the oceanographic surveys conducted by the National Oceanic and Atmospheric Administration and other agencies. No proprietary data were available to this study, although both agency and industry reviews of important technical, geologic, and economic assumptions were made.

The principal data gaps include:

- Oceanography -- Data on the seasonal extent and annual variation of landfast ice and multiyear pack ice coverage for the Chukchi Sea are still limited. Even more limited are data on dynamic ice movement and forces generated, critical data for platform design and overall production feasibility.

- Petroleum Geology -- Geophysical data for the Barrow Arch planning area are extremely limited and deficient. Seismic data is of a reconnaissance nature and was collected from U.S. Coast Guard icebreakers with limited equipment. Seismic lines obtained are few and relatively short. No attempts were made to define structural traps. In addition, seismic coverage of the Chukchi Sea was limited by ice coverage in several areas. While more recent geophysical data has been obtained by the U.S. Geological Survey, it had not been analyzed at the time this report was prepared.

- Facility Cost -- The petroleum facility cost estimates (for platforms, pipelines, terminals, etc.) are tentative; no petroleum exploration and production has yet taken place with the same conditions that may provide direct operational and cost experience.

1.4 Report Content and Format

This report was written as one of two reports assessing oil and gas development technologies for the two proposed Chukchi Sea lease sale planning areas. In addition to the Barrow Arch planning area, which is the subject of this report, the Hope Basin planning area, recently deleted from the Interior Department's proposed 5-year OCS oil and gas leasing schedule, was also studied. The study methodology is basically the same as that employed by Dames & Moore in preparing previous petroleum technology assessments for other Alaska OCS lease sale planning areas. However, the report's analytical approach was structured to accommodate both Chukchi Sea study areas. While appropriate sections of previous studies in this series are incorporated by reference, the basic data set for this analysis is unique to the Chukchi Sea and was specifically assembled for this report. Contrasts between this area and other Alaska OCS lease sale areas have been identified where appropriate.

This report commences with a summary of findings (Chapter 2.0). The results of the petroleum technology assessment are presented in Chapter 3.0. Onshore sites for petroleum facilities are discussed in Chapter 4.0. Chapter 5.0 details the manpower requirements by task, activity, and facilities for the particular technologies described in Chapter 3.0. The results of the economic analysis are presented in Chapter 6.0. Chapter 7.0, based upon the resources estimates for the central Chukchi shelf assembled by the National Petroleum Council (1981) concludes the main body of the report with a description of a hypothetical development case.

Appendix A presents a description of the Barrow Arch petroleum geology and the reservoir assumptions of the technology assessment. Appendix B gives the economic parameters, petroleum development costs and scheduling assumptions upon which the economic analysis is based.

2.0 SUMMARY OF FINDINGS

Throughout the course of this study, we have selected assumptions regarding oil production characteristics, schedules and economic parameters that are realistic but favorable for Barrow Arch planning area oil development. Therefore, our findings should be used with these favorable assumptions in mind.

2.1 Petroleum Geology

The Barrow Arch planning area covers a vast area of outer continental shelf below the Chukchi Sea. Within this area, we have identified three zones with favorable prospects for hydrocarbon accumulation. The most favorable is located in the geologic subregion referred to as the central Chukchi shelf (Figure 2-1). This includes a very thick sedimentary section and many anticlines in the offshore extension of the Colville Trough -- the province of North Slope oil and gas. The most promising area in the central Chukchi shelf is along the northern coast. This area is also attractive for petreolum development because much of it is nearshore, extending from the shoreline across the shallowest federal waters. Within this coastal strip, the northern sector of the central shelf is by far the most favorable of all the Chukchi Sea.

Two other zones with petroleum potential were considered secondary candidates for oil development. One is the southern part of the central Chukchi shelf, which is an overthrust zone associated with the Herald Arch. The other is the north Chukchi shelf, which is comprised of great thicknesses of (inferred) Cretaceous and Tertiary rocks containing shale diapirs. This latter zone is in deeper water, further from shore and to the north.

Our study concentrated on conditions in the most favorable area on the validated assumption that major petroleum finds would be needed to encourage initiation of petroleum development in this arctic region. It does indeed appear geologically possible that a giant oil field (on the order of one

Source: National Petroleum Council 1981; Webster 1982.

Figure 2-1
ARCTIC OFFSHORE OIL & GAS PROVINCES

billion barrels) could occur in this zone. Potential reservoir rocks here include major North Slope producers such as the Sadlerochit Formation and the Kuparuk River sandstones.

These reservoirs should range from 1,500 to 7,500 meters (5,000 to 25,000 feet) deep with an average well depth of around 3,000 meters (10,000 feet), which is favorable for maximum drainage from a single platform.

A USGS resources report has not been published specifically for Barrow Arch planning area at this writing. From our analysis of the petroleum geology, including conversations with USGS and review of the National Petroleum Council (1981) estimates, we utilized the following tentative values for the central Chukchi shelf:

Oil	1.5 billion barrels
Gas	4.5 trillion cubic feet.

2.2 Environmental Constraints

There are several stringent environmental characteristics of the Barrow Arch planning area, and the clearly dominating factor constraining offshore activities is sea ice. Great forces are generated by moving ice, and in this area the strong multi-year pack ice is the controlling design parameter. The sea ice also constrains marine construction operations since most of these require open-water conditions; the open-water season is brief and its duration unpredictable.

When the sea ice has retreated, there is then the potential for large storm waves. Fog is also most common during the summer season. There are virtually no natural harbors along this entire 700-kilomter (450-mile) coastline that offer significant depths and protection, only some shallow lagoons behind low barrier beaches.

Storms and extremely low temperatures will reduce the efficiency and increase attention to safety for all operations in this area.

Water depths in the Barrow Arch planning area range from 10 to 100 meters (30 to 300 feet) -- not great by world standards of offshore oil operations. However, even shallow depths are costly to develop because of the sea ice. The seafloor is generally of low relief; it can be characterized as having a narrow nearshore strip, about 15 meters (50 feet) deep, along the 3-mile state-federal offshore boundary and a large area beyond that averaging close to 37 meters (120 feet) of water. The transition zone between these typical depths occurs over a relatively short distance; 27 meters (90 feet) is a representative depth for this thin zone. Thirty meters (100 feet) may be considered the start of "deep water" conditions for offshore development in the Chukchi Sea.

Seafloor conditions are believed to consist of generally stable clastic sediments. Some areas of sands and gravels, desirable as construction materials, occur in the area, particularly nearshore. Seismic activity is not unknown, but is low.

Environmental hazards in the area include bottom scour from pressure ridges and tabular icebergs, river flooding of shorefast ice, strudel scouring, high storm tides, rapid currents in tidal passes, rapid coastal erosion, ice ride-up and override events.

Remoteness and the complete lack of infrastructure will also constrain exploration operations and production developments. This and other environmental conditions require that if any oil is delivered from this area, it will entail major projects.

2.3 Petroleum Technologies and Production Strategies

Unlike non-arctic OCS areas, the Barrow Arch planning area will include exploration technologies of a scale and magnitude approaching that of the production platforms elsewhere. Exploration techniques appropriate to Chukchi Sea conditions have begun to be applied in the Canadian and Alaska Beaufort Sea. Exploration drilling at shallower sites will rely mainly on artificial fill islands (with caisson-retained designs being more favored as depths increase) and special arctic drilling platforms that are bottom-founded, especially towards the north. More conventional exploration from ice-designed floating drilling platforms will be considered, especially towards the south; these will have to restrict their schedules around the short open-water season and are limited by shallow waters since a minimum depth is necessary for floating drilling. Based on information published by the National Petroleum Council (1981), oil and gas resources are not considered recoverable with present technology in areas of Arctic pack ice where water depths are greater than 60 meters (200 feet).

Marine support bases will have to be built from scratch at remote sites. Dredging may be needed to provide suitable harbor facilities.

Production platforms will be either artificial fill construction or a concrete or steel monocone design. The latter would be constructed in a deepwater shipyard and towed to the site for installation. These designs provide ice resistance by breaking the floes in flexure (rather than crushing ice-like Cook Inlet-type designs).

Artificial fill islands will most likely be constructed by dredging methods using coarser sediments from nearby seafloor sources. Unretained natural (angle-of-repose) slopes must be provided protection from ice and wave attack, and these islands will be used mainly in shallower sites. Caisson-retained fill islands may be used for shallow or deep sites and will be the favored design for deeper areas. This concept is intermediate in construction techniques, requiring shipyard manufacture, tow-out, and fill placement. Dredging will be needed to both fill the cassion and to provide an underwater berm to set it on.

The two transportation modes -- tankers or pipeline -- have relatively restricted options in the Chukchi Sea for their implementation. Ice-breaking tankers will require a marine terminal constructed for sea ice operation. In the Barrow Arch planning area, there are no ideal natural sites for such a facility, and the most favorable conditions are found to the north in the Wainwright vicinity.

Ice-breaking tankers would be a dedicated fleet to carry Chukchi Sea oil to an Aleutian Island transshipment terminal. From there the oil would be moved to market in very large crude carriers (VLCC).

Marine pipelines must be constructed if the oil is to come ashore for tankers or for onshore pipeline transport to market. These offshore pipelines must be buried over most of their length to protect them from moving ice keels. Nearshore routes and shoreline crossing are not only vulnerable to frequent and deep ice-gouging, they may also encounter subsea permafrost conditions. Further, the marine pipelines can be constructed only during the open-water season.

A major onshore arctic pipeline to carry Chukchi Sea oil to market would be similar in concept and effort to the proven trans-Alaska pipeline system (TAPS). This analysis focuses on the scenario of a 500-kilometer (300-mile) pipeline running eastward across the North Slope to link up with the existing TAPS. A shorter overland pipeline southward to a new marine terminal at Cape Thompson is also addressed in connection with a discovery toward the southern central Chukchi shelf.

The APLA (for artificial [or arctic] production and loading atoll) concept combines production platform and marine terminal functions in a single massive offshore facility. This concept would be constructed by new very high capacity dredging operations and would require significant seafloor sources of fill materials.

Tanker loading in the presence of ice, whether offshore or at a coastal site, is an operation requiring experience with specific new designs.

2.4 Manpower

Manpower needs for Chukchi Sea offshore exploration, construction and production tasks have been estimated in this study. Significant considerations are the harsh arctic conditions, strong seasonal constraints on construction period, and the remoteness requiring long transit to the area and the need for enclave living. The labor needs and conditions are generally analogous to the establishment of the Prudhoe Bay field.

All phases of offshore petroleum development will probably take longer to accomplish than similar operations elsewhere.

2.5 Economics of Oil and Gas Development

The economic feasibility of developing discovered oil in the central Chukchi shelf of the Barrow Arch planning area is very much associated with mega-concepts -- mega-fields, mega-dollars, and mega-production and transportation hurdles. Production technologies, although technically feasible, are extremely costly even in the more favorable geologic and environmental locations. Hence, billion-barrel fields show only marginal economic results given the assumptions and estimated values used in this analysis.

Our analysis indicates that development of a very nearshore billion-barrel field offers a real after-tax rate of return (ROR) of about 10 percent and would cost approximately $6 to $7 billion (1982) to develop. At the 37-meter (120-foot) water depths more typical of the central Chukchi shelf, ROR's are on the order of 8 percent for an investment of about $8 billion (1982).

Assuming a 12 percent real after-tax hurdle rate is sufficient to attract multi-billion dollar oil industry investments in the Chukchi Sea, minimum field sizes to justify development will have to exceed 1.0 billion barrels (about 1.25 billion in shallow water and 1.5 billion in deeper waters).

In general, the caisson-retained gravel islands and concrete monocones appear to be economically preferred offshore systems. Unretained gravel islands are attractive in only the shallower waters. APLA's are so expensive as to be uneconomic at this time.

In order for the deeper water portions of the Barrow Arch planning area to become commercial, an offshore loading system more cost-effective than the APLA must be developed. If such a system were developed, it might also render the central Chukchi shelf more economic by obviating the need for costly shore terminals and pipelines.

Assuming that offshore oil development does occur (and barring a breakthrough in technology of offshore loading in sea ice), our analysis shows that a pipeline to TAPS is competitive with an ice-breaking (Class 7) shuttle tanker fleet for transporting crude to an ice-free VLCC port. If more detailed cost analyses bear out our estimates, the decision between the two approaches may turn not on economics, but on the trade-off between the environmental considerations of a long onshore arctic pipeline connecting the Barrow Arch planning area to TAPS versus the risks of tanker operations in the ice-infested waters of the Chukchi and Bering Seas.

Even giant natural gas fields (in the 4 trillion cubic feet range) are far from commercial under current technologies and prices. Under the most favorable conditions, our analysis indicates real, after-tax ROR's in the 5 to 7 percent range. Even substantially larger gas fields would not show appreciably higher rates of return because the largest cost components -- offshore equipment and tankers -- offer only limited economies of scale. For gas resource development to become economic, either a 50 percent (real) cost escalation in gas prices or a technical break through in gas transportation systems is required. This means gas would have to sell in excess of $10.00 per thousand cubic feet in 1982 dollars.

It is essential to keep in mind the large number of interactive assumptions and estimated parameter values that drive our economic analysis. A great many geologic assumptions, estimated platform and reservoir engineering considerations, as well as prices and costs, are derived in our research. In most cases the values for the variables that drive the economic results are realistic but favorable. Thus, our results are optimistically biased. The analysis is done in constant 1982 dollars; that is, the relationship between prices and costs is assumed to hold constant. The oil price assumed is $31.50 FOB Aleutians. LNG, valued at its diesel equivalent, is assumed to be worth $6.75 per thousand cubic feet, C.I.F. southern California. To the extent that energy prices escalate faster than development costs, our results are conservative, and development would be more favorable than indicated. If, however, costs inflate faster than energy prices, our results become even more optimistic.

3.0 RESULTS OF THE PETROLEUM TECHNOLOGY ASSESSMENT

3.1 Introduction

The technology assessment for the Barrow Arch planning area has four major elements:

- o An assessment of the environmental forces and operating conditions that will influence the design, selection and location of offshore facilities, including platforms and pipelines, and the overall field development and transportation strategy.

- o A description of selected field development components, their design parameters and installation techniques.

- o Identification of field development strategies that may be adopted to develop oil and gas resources in the eastern Chukchi Sea. The field development strategy involves the sum of the various field development components (platforms, wells, process equipment, pipelines, terminals, etc.) and the transportation system for either oil or gas. Included in this evaluation is a discussion of such areas as: trade-offs between artificial islands and other platforms, ice-breaker tanker transport vs. pipelines to ice-free ports, techniques to develop marginal fields, and the application of subsea systems.

- o Identification and selection of field development components and strategies as scenarios to be used for the economic analysis.

In previous technology assessments in this series, Dames & Moore has presented more detailed descriptions of different types of arctic and sub-arctic petroleum technologies. The reports on Beaufort Sea Petroleum Development Scenarios (Dames & Moore 1978) and Bering-Norton Petroleum

Development Scenarios (Dames & Moore, 1980a) contain an extensive discussion of arctic and sub-arctic petroleum technologies. These reports presented descriptions of artificial islands, cones and monocones that are relevant to this study. Rather than reiterate these descriptions, the reader is referred to these technical discussions that provide background for the conclusions in this report.

From this broad evaluation of arctic oil and gas technologies, a subset of specific exploration, production and transportation technologies and systems tailored to the environment and operational conditions of the Chukchi Sea was selected. Assembled into a technology model incorporating assumptions about field size, location and alternate production strategies, it formed the basis for the economic analysis contained in Chapter 6.0. Each of the technological components included in this subset for economic analysis is discussed later in this chapter.

This chapter commences with an evaluation of environmental constraints. It is important to note that this discussion of environmental constraints is based upon current, publicly available data. In comparison to other OCS lease sale planning areas, this data base is very limited. In particular, data on sea ice characteristics and behavior, critical factors affecting exploration and production concepts, are very limited. Our study team includes industry expertise in sea ice engineering to provide experienced judgment regarding ice design parameters. Several proprietary data collection efforts by industry have been completed or are being planned; however, these were not available for this analysis, hence our conclusions should be regarded as preliminary. In particular, our approach with respect to platform design and operational constraints is conservative. The chapter concludes with a discussion of field development strategies for the Chukchi Sea that warrant economic evaluation.

3.2 Environmental Constraints to Petroleum Development

3.2.1 Meteorology and Oceanography

3.2.1.1 Meteorology

The climate of Alaska's northern and northwestern coast is classified as arctic by the National Weather Service. Summer weather is characterized by cool marine winds, frequent but light precipitation and considerable cloudiness and fog. In winter the cloudiness decreases and very cold winds prevail. A light snow cover is established by mid-September and persists until June or July. Below freezing air temperatures are the rule except in June, July, August and early September.

Although meteorological information has been systematically collected in the Arctic from coastal stations since World War II, available data records are still somewhat limited, relative to sub-arctic OCS areas. Particularly lacking are data from offshore areas due to the limited vessel traffic in the area. Nevertheless, a reasonable picture of the area's general meteorological setting has been assembled.

Air temperatures in the lease sale region tend to be persistently low for most of the year. The U.S. Coast Pilot for the Arctic Ocean area provides a general description of the region's weather. Winters are cold and summers are cool. In November, average daily maximums drop to around -10°C (14°F) or below, while average minimums are around -18°C (0°F). February is generally the coldest month. Average maximums range from just above -17°C (1°F) at Kotzebue to -25°C (-13°F) east of Cape Lisburne. Low temperatures in the -30°C (-22°F) range are common. Extremes of -45°C (-49°F) or colder have been recorded.

Table 3-1 lists representative temperature information for several coastal stations along the northern Chukchi Sea coast. Air temperatures over the arctic land mass are less stable than those over the polar ice pack; air temperatures over the pack ice are usually uniform and deviate little from day to day. In summer the temperature over the pack ice remains relatively stable, near the freezing point.

Annual precipitation over most of the arctic coastal region is very light, ranging from 10 to 40 centimeters (4 to 16 inches) annually in the northern Chukchi Sea. Annual snowfall can range from 30 to 150 centimeters (12 to 59 inches) depending upon location and elevation. Some form of measurable precipitation falls on about 200 to 300 days per year, with

TABLE 3-1

AIR TEMPERATURES AT ARCTIC COASTAL STATIONS

Station	Mean Annual °C (°F)	Summer Seasonal Maximum °C (°F)	Winter Seasonal Maximum °C (°F)	Record High °C (°F)	Record Low °C (°F)	Mean Number of Days 0°C (32°F) or Below
Cape Lisburne	-7.8 (18.0)	11.1 (52)	-28.9 (-20)	23.3 (73.9)	-43.9 (-47.0)	268
Point Lay	-10.6 (12.9)	11.6 (53)	-32.7 (-27)	25.6 (78.1)	-48.3 (-54.9)	284
Wainwright	-11.8 (10.8)	10.0 (50)	-31.1 (-24)	26.7 (80.1)	-48.9 (-56.0)	306
Barrow	-12.6 (9.3)	7.2 (45)	-31.1 (-24)	25.6 (78.1)	-48.9 (-56.0)	324

Sources: Brower et al. (1977)
Swift et al. (1974)

heaviest precipitation in July, August and September, averaging 5 to 10 centimeters (2 to 4 inches) each month (U.S. Coast and Geodetic Survey 1979). Snow can appear in any month and usually predominates beginning in September (Arctic Institute of North America 1974). Table 3-2 provides data on precipitation measurements at coastal stations.

The relative humidity is generally high with values averaging from 60 to 90 percent throughout the year. However, the absolute humidity is very low due to the low air temperatures, which prevent water vapor buildup in the atmosphere, and the ice cover, which limits evaporation. Other types of precipitation experienced include rime or granular ice, which occurs over most arctic coastal regions throughout the year, and hoarfrost, which occurs in winter (Arctic Institute of North America 1974).

Wind conditions tend to be fairly constant along the arctic coast year-round. The Arctic Institute of North America (1974) reports that a general yearly average for the coastal zone is 24 to 32 kilometers/hour (15 to 20 miles/hour) at relatively exposed locations. Table 3-3 summarizes surface wind data compiled by Swift et al. (1974) for coastal stations along the northern Chukchi Sea. Observational data summarized by Brower et al. (1977) indicate that 45 percent of all observations reported winds less than 19 kilometers/hour (12 miles/hour) and 5 percent of all observations reported winds less than 6 kilometers/hour (4 miles/hour).

High winds may occur at any time of the year although maximum velocities have historically occurred in the coldest months. Gales occur about 2 percent of the time in the northern Chukchi Sea (U.S. Coast and Geodetic Survey 1979).

Brower et al. (1977) estimates that the 100-year wind speed may exceed 179 kilometers/hour (111 miles/hour) in the northern Chukchi Sea. Sustained winds of 93 to 105 kilometers/hour (58 to 65 miles/hour) have been recorded with gusts going much higher (Swift et al. 1974). In addition to the design parameters affected by surface winds, ambient wind conditions during the summer occasionally drive the pack ice into nearshore areas. This

TABLE 3-2

PRECIPITATION AT ARCTIC COASTAL STATIONS

Station	Liquid Precipitation (cm) Annual Mean	Liquid Precipitation (cm) Monthly Maximum	Liquid Precipitation (cm) 24-Hour Maximum	Snow (cm) Annual Mean	Snow (cm) Monthly Maximum	Snow (cm) 24-Hour Maximum
Cape Lisburne	37.3	17.7 (Aug)	4.5 (Aug)	152.4	--	27.9 (Nov)
Point Lay	16.7	15.7	3.8	50.8	--	--
Wainwright	12.7	23.6 (Aug)	10.1 (Jul & Aug)	30.4	30.4 (Oct)	--
Barrow	10.9	7.1 (Aug)	2.5 (Oct)	73.6	66.0 (Apr)	38.1 (Oct)

Source: Swift et al. (1974)

TABLE 3-3

SURFACE WINDS AT ARCTIC COASTAL STATIONS

Station	Winter		Summer		Maximum Recorded	
	Prevailing Direction	Mean Speed (km/hour)	Prevailing Direction	Mean Speed (km/hour)	Prevailing Direction	Speed (km/hour)
Cape Lisburne	E, SE	21	E, NE, SW	19	--	>105
Wainwright	E	--	E, SW	--	--	--
Barrow	E, NE	18	E	19	W	93

Source: Swift et al. (1974)

relatively rapid shift in the pack ice can adversely affect vessel and barge movements or other offshore activity associated with oil and gas exploration and development.

Fog is the major restriction to visibility in the Arctic. Dense fog can be expected to occur from 30 to 100 days each year along the coast. Offshore and inland areas are much less prone to fog. Advection or sea fog is the primary restriction to visibility during the warmer months of the year. It is most prevalent from June through September, and is most dense during the morning hours. Areas along the coast may have advection fog for up to 15 to 20 days per month in summer (Arctic Institute of North America 1974). In July and August, visiblities drop below 3.2 kilometers (2 miles) 10 to 25 percent of the time (U.S. Coast and Geodetic Survey 1979). Advection fog, provided by relatively warm, moist air moving over a cold surface, tends to persist due to strong temperature inversions that prevent turbulent dissipation (Energy Interface Associates 1979).

During winter, radiation fog, ice fog and steam fog can all reduce visibility. Table 3-4 presents annual and monthly data on fog conditions at coastal stations. It is apparent from the data that there are wide variations in visibility limitations imposed by fog due to both season and location. In general, summer fog conditions tend to be about twice as bad as winter conditions at coastal stations. However, winter visibilities can be reduced to less than 0.8 kilometers (0.5 miles) by snow or blowing snow (U.S. Coast and Geodetic Survey 1979). Cloudiness is another prevalent condition along the entire arctic coast that tends to reduce visibility. Energy Interface Associates (1979) report that over 60 percent of the days are cloudy on an annual basis. During the summer and early fall, cloudiness occurs more than 70 percent of the time.

3.2.1.2 Bathymetry

The Chukchi Sea is shallow with a mean depth of about 40 meters (130 feet), having gentle knolls and several shallow troughs but with a relief that is a substantial fraction of the mean depth (Paquette and Bourke 1981).

TABLE 3-4

FOG CONDITIONS AT ARCTIC COASTAL STATIONS
(Percent Frequency of Occurrence Based on Hourly Observations)

Station	Annual	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Cape Lisburne	12.3	8.1	10.5	11.7	13.5	16.6	22.8	18.6	18.8	11.3	5.2	4.4	6.1
Barrow	15.8	12.5	13.1	7.9	9.3	17.4	26.4	25.9	25.5	17.7	13.0	10.5	10.4

Source: Brower et al. (1977)

The central Chukchi shelf, which extends northwestward from the coastline between Cape Lisburne and Point Barrow to the 50-meter (165-foot) isobath, is a shelf of low relief. A broad north-south trending trough 50 meters (165 feet) deep lies between the mainland and Herald Shoal (McManus et al. 1964). In this area, nearshore depths along the coast are usually less than 20 meters (66 feet) and remain less than 60 meters (200 feet) throughout most of the shelf. The maximum recorded depth is 70 meters (230 feet).

The offshore area between Icy Cape and Cape Lisborne is shallow (less than 25 meters [80 feet]), very flat and featureless. Gradients are extremely gentle, averaging less than 3 meters/kilometer (10 feet/mile) across the shelf (Toimil 1979). The only relatively steep nearshore bottom topography occurs between Point Belcher and Point Franklin where depths reach 40 meters (130 feet) within 8 kilometers (5 miles) of shore. Nearshore depths in the Chukchi Sea are maintained by currents and altered by seasonal ice gouging. Storm actions shift sand spits and shoals considerably, but there is little evidence of storm waves affecting deeper areas (Alaska Department of Fish and Game 1982).

As shown on Figure 3-1, Hanna Shoal (30 to 40 meters [100 to 130 feet]) lies to the northeast and another 40-meter (130 foot) shoal lies approximately at 71° N, 165° E. To the east, the Barrow Canyon parallels the northwest coast of Alaska. The northern section of the Barrow Arch, which extends approximately to the 100-meter (330-foot) isobath, includes the Herald Canyon, a shallow trough that lies at about 175° W and is much less notable than the Barrow Canyon (Paquette and Bourke 1981).

3.2.1.3 Circulation

The circulation within the Chukchi Sea is known only in the most general fashion, having been inferred from water mass studies reinforced by infrequent, short-term current meter measurements with some support from the concept of bathymetric steering (Paquette and Bourke 1981).

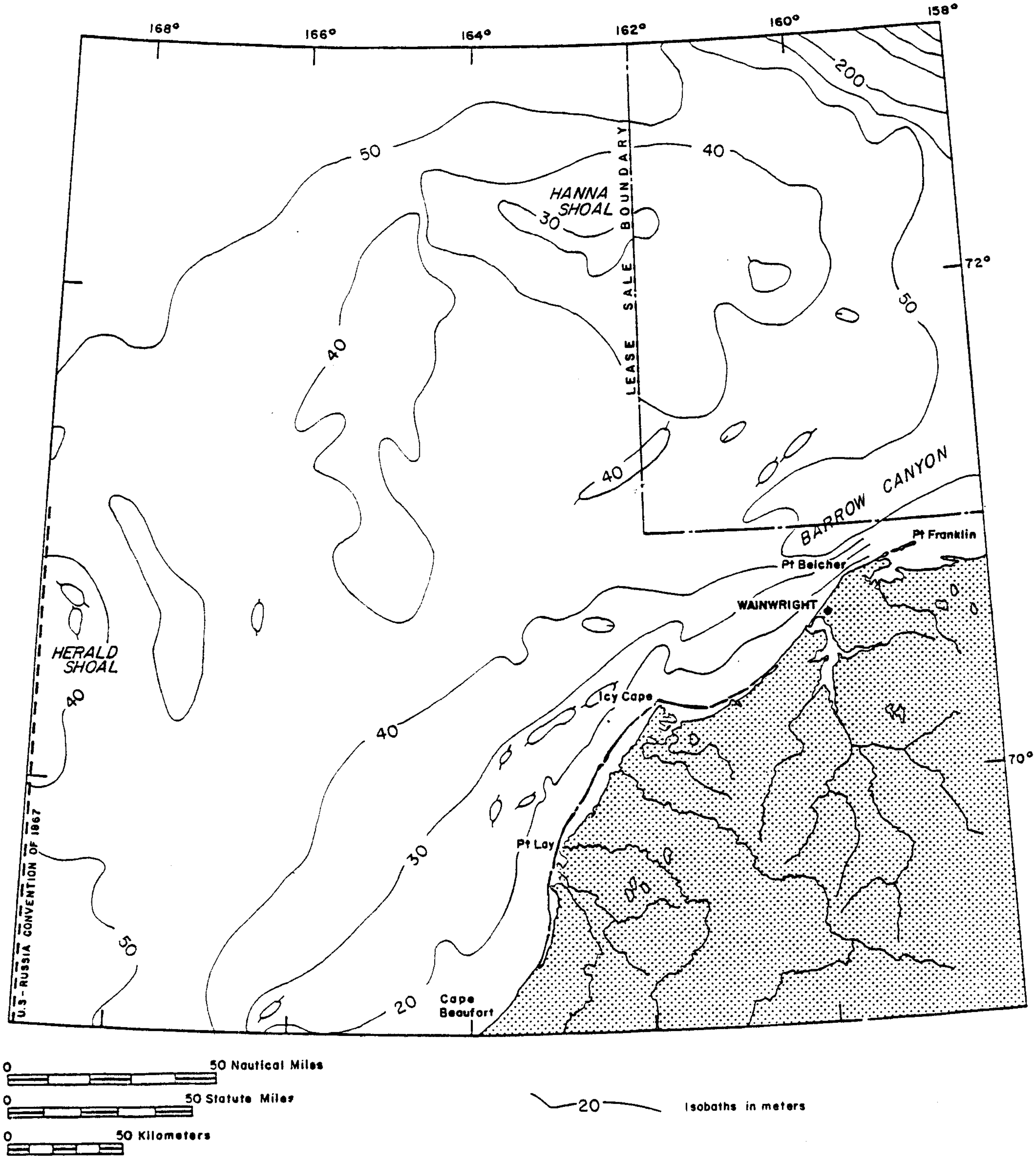


Figure 3-1

BATHYMETRY OF THE NORTHEAST CHUKCHI SEA

Source: Adapted by Dames & Moore from Schumacher (1976).

Although the Chukchi Sea is part of the Arctic Basin, its currents are dominated by the northward flow of water from the Bering Sea. Detailed measurements show that the flow is predominately barotropic, with speeds and directions uniform from top to bottom (Arctic Institute of North America 1974). A pressure-induced, north-sloping sea surface is thought to cause the northward flow of water from the Bering Sea to the Arctic Basin (Wilimovsky and Wolfe 1966). In 1945, Russian scientists reported average current speeds of 45 centimeters/second (1.5 feet/second) during summer and 10 centimeters/second (0.3 feet/second) in winter. The direction of the primary current is generally parallel to the coast, with eddies and reversals noted in nearshore areas. Winds have been observed to slow the current, occasionally reversing its direction through the Bering Strait (Arctic Institute of North America 1974).

Figure 3-2 illustrates patterns of flow in the Chukchi Sea. In general, Coachman et al. (1975) indicate that warm waters entering the Chukchi Sea through the eastern side of the Bering Strait at estimated flow speeds from 30 to 150 centimeters/second (1 to 5 feet/second) flow northward and turn west-northwest in a broad stream starting from south of Point Hope. Near shore, a northeasterly stream branches from this flow in the vicinity of Cape Lisburne. The westerly branch, moving at 15 centimeters/second (0.5 feet/second), enters the Arctic Ocean by way of Herald Canyon. The northeasterly branch narrows into a high-speed jet-like stream, moving from 25 to 30 centimeters/second (1 foot/second), approximately along the 40-meter (130-foot) isobath north of Cape Lisburne and then close to the Alaska coast between Wainwright and Point Barrow, where it flows eastward into the Beaufort Sea. Dubbed the Alaska Coastal Current by Paquette and Bourke (1974), currents on the outer shelf form a regime that is highly energetic over a broad band of sub-tidal frequencies, with a mean eastward flow affected by local bathymetry (Coachman et al. 1975).

Within this general picture of the circulation regime, significant uncertainties and variations exist. Ingham et al. (1972), in a set of observations in the fall of 1970, indicate that currents were strongly influenced by the northeasterly winds and showed the expected northeastward

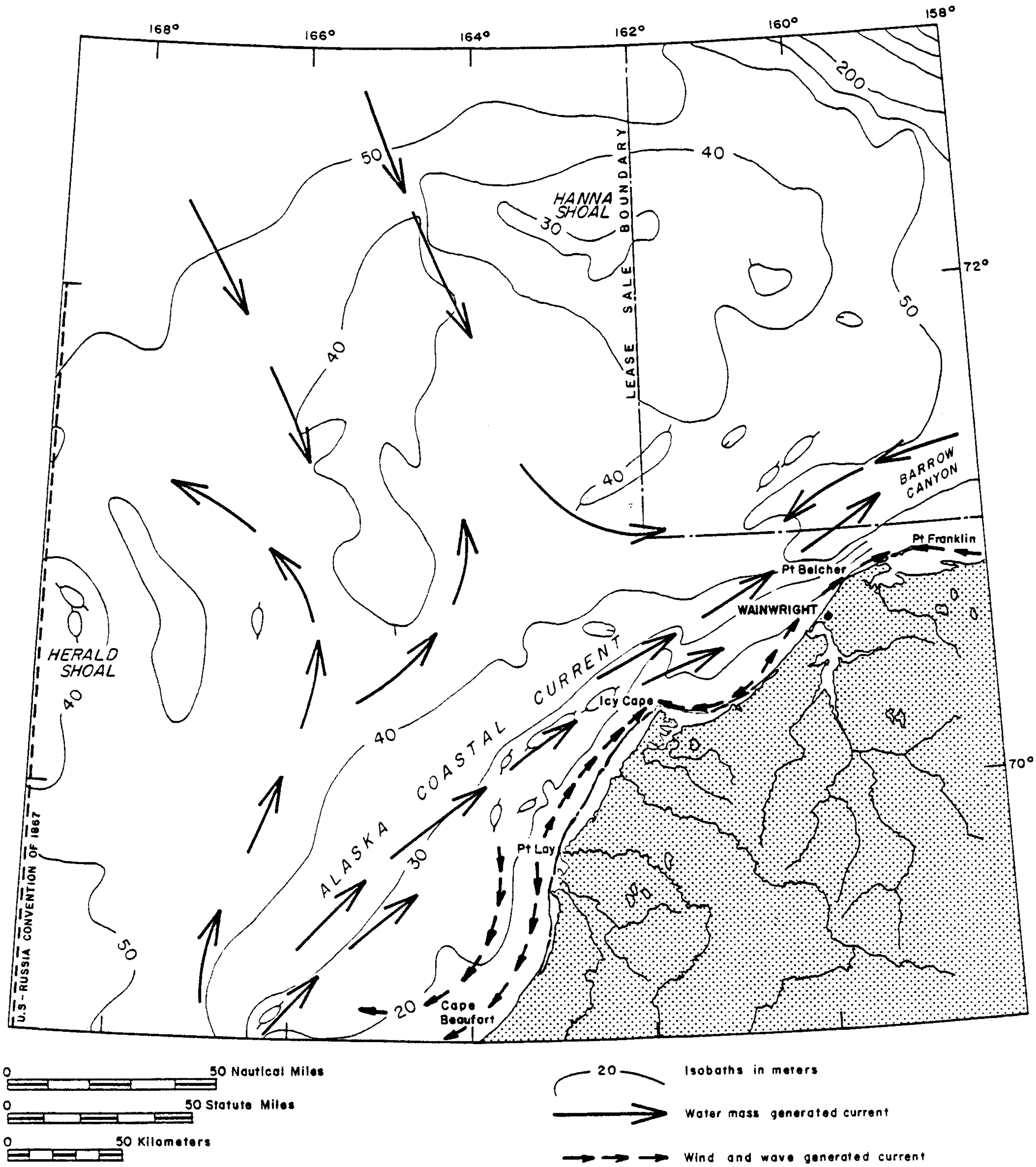


Figure 3-2

SURFACE CURRENTS IN THE NORTHEAST CHUKCHI SEA

Sources: Adapted by Dames & Moore from Coachman, Aagaard and Tripp (1976); Garrison (1976); Hufford (1977a); Paquette and Bourke (1974); Schumacher (1976); Searby and Hunter (1971).

set only when winds were weak and variable. Their observations also indicated that returning nearshore southwesterly currents between Cape Lisburne and Icy Cape were weak and variable. Hufford (1977) reports the existence of a significant offshore southwesterly current beyond the Alaska Coastal Current in the vicinity of Point Franklin. The U.S. Coast and Geodetic Survey (1979) reports that another current moves northwest out of Kotzebue Sound and joins the Alaska Coastal Current in the vicinity of Cape Krusenstern, producing a resultant velocity of 75 to 100 centimeters/second (2.5 to 3.3 feet/second) at Point Hope in July and August. They report that during summer months, the Alaska Coastal Current moves at 50 centimeters/second (1.7 feet/second) after rounding Point Hope. They also indicate that currents are influenced not only by the wind, but by moving pack ice, with currents stopped completely by landfast ice.

3.2.1.4 Tides and Storm Surges

Almost no work on the tides of the Alaska arctic coast has been published. Astronomic tides are very much smaller than meteorological tides (OCSEAP 1978). Along the northern Chukchi coast, astronomic tides are reported to be small, averaging approximately 30 centimeters (1 foot) (Arctic Institute of North America 1974). The mean tidal range at Wainwright is reported to be 15 centimeters (6 inches), according to Bechtel (1979), while tides at Kiwalik in Kotzebue Sound are reported at 80 centimeters (2.7 feet) by Stringer (1978a,b).

Deviations in sea level produced by meteorological forces are a significantly greater problem than tides in the Barrow Arch planning area. These deviations, known as storm surges or storm tides, are produced by wind stresses and barometric pressure gradients acting on the water surface (Energy Interface Associates 1979). The dominant storm track producing storm surges is to the northeast, from storm systems originating in the Aleutian chain and moving through the Bering Strait (U.S. Navy 1968). An occasional storm moving eastward from the Siberian Shelf may produce surges. The most severe surges, often accompanied by high waves, occur during September and October when storm frequencies are highest and open water exists (OCSEAP 1978).

Chukchi Sea is ice-covered. Since the pack ice retreats a relatively short distance offshore during most summers, the wave climate is characterized by low, short-period waves (except during storms) with winds that blow parallel to the coast (Energy Interface Associates 1979). Wave heights of 6 meters (20 feet) or more occur less than 1 percent of the time during the ice-free season (Brower et al. 1977).

The extreme wave conditions for the Chukchi Sea have been calculated (Brower et al. 1977). These data suggest that the 10-year storm (i.e., a storm with a long-term average recurrence interval of once every 10 years) will have sustained winds of 75 knots and extreme wave heights of 23.5 meters (77 feet). The 50-year storm will have corresponding values of 90 knots and 31 meters (102 feet). Calculated 100-year return period values are 97-knot winds generating significant wave heights of 19.5 meters (64 feet) with maximum waves 35 meters (115 feet) high. However, these extreme wave heights for the Chukchi Sea were calculated based on the work of Thom (1973a,b) and do not allow for the probability that the wind fetch and wave height are reduced by the presence of ice cover. In our judgment, extreme waves on the order of one-half of these values would be closer to realistic design parameters, for deepwater conditions.

Nearshore, where depths limit waves, the values will be even lower. Heideman (1979) calculates that for a 100-year return period at a 9-meter (30-foot) water depth inside a Beaufort Sea barrier island, a storm surge of 2 meters (6.6 feet) is accompanied by a maximum wave height of only 8.2 meters (27 feet). Heideman's analysis relied on two proprietary storm hindcast studies prepared by Joy (1978, 1979). For the Chukchi Sea, a conceptual design study of an arctic terminal for ice-breaking tankers (Bechtel 1979) arrived at wave oceanographic design data for 37-meter (120-foot) water depths off of Wainwright on the northern Chukchi Sea coast. Calculated wave parameters were a storm surge of 3.3 meters (11 feet), a significant wave height of

Along the Chukchi Sea coast and Kotzebue Sound coast, surges are possible from mid-June through November. The Chukchi Sea coast is most susceptible to storm surge damage from northward moving storms from the Bering Strait, while Kotzebue Sound is affected by storm surges and coastal flooding from westerly Siberian storms with winds in excess of 75 kilometers/hour (45 miles/hour; Brower et al. 1977). Storms causing the most extensive flood damage require a long fetch and little or no ice cover. Storm surges are also greater when the air temperature is colder than the water.

Negative surges, which are usually smaller than positive surges, also occur and appear to be more frequent in winter. Negative surges are potentially hazardous to vessel traffic in the Arctic due to the relatively shallow water depths that provide limited draft clearance in many areas. A few observations of negative surges indicate that they are smaller than positive surges, on the order of 1 meter (3 feet) or less (Energy Interface Associates 1979).

There are no direct measurements of storm surge elevations, but secondary observations of strandlines above the coastal beaches provide evidence of their general magnitude. The most severe recorded storm in 1963 produced a storm surge of 3 meters (10 feet) plus waves of the same height (Brower et al. 1977). The surge produced extensive coastal flooding, ice grounding and shoreline erosion in the vicinity of Barrow (Hunkins 1965).

Thirteen storm surges have been documented in the Chukchi Sea area since 1960. Although insufficient data exist to develop recurrence intervals for storm surges, Reimnitz and Barnes (1974) record that local Eskimos report such severe positive surges at around 25-year intervals.

3.2.1.5 Waves

Wave generation in the Chukchi Sea is limited to the summer open-water season. No significant wave activity exists from November to May when the

Chukchi Sea is ice-covered. Since the pack ice retreats a relatively short distance offshore during most summers, the wave climate is characterized by low, short-period waves (except during storms) with winds that blow parallel to the coast (Energy Interface Associates 1979). Wave heights of 6 meters (20 feet) or more occur less than 1 percent of the time during the ice-free season (Brower et al. 1977).

The extreme wave conditions for the Chukchi Sea have been calculated (Brower et al. 1977). These data suggest that the 10-year storm (i.e., a storm with a long-term average recurrence interval of once every 10 years) will have sustained winds of 75 knots and extreme wave heights of 23.5 meters (77 feet). The 50-year storm will have corresponding values of 90 knots and 31 meters (102 feet). Calculated 100-year return period values are 97-knot winds generating significant wave heights of 19.5 meters (64 feet) with maximum waves 35 meters (115 feet) high. However, these extreme wave heights for the Chukchi Sea were calculated based on the work of Thom (1973a,b) and do not allow for the probability that the wind fetch and wave height are reduced by the presence of ice cover. In our judgment, extreme waves on the order of one-half of these values would be closer to realistic design parameters, for deepwater conditions.

Nearshore, where depths limit waves, the values will be even lower. Heideman (1979) calculates that for a 100-year return period at a 9-meter (30-foot) water depth inside a Beaufort Sea barrier island, a storm surge of 2 meters (6.6 feet) is accompanied by a maximum wave height of only 8.2 meters (27 feet). Heideman's analysis relied on two proprietary storm hindcast studies prepared by Joy (1978, 1979). For the Chukchi Sea, a conceptual design study of an arctic terminal for ice-breaking tankers (Bechtel 1979) arrived at similar wave data for 37-meter (120-foot) water depths off of Wainwright on the northern Chukchi Sea coast. Calculated wave parameters were a storm surge of 3.3 meters (11 feet), a significant wave height of

5.4 meters (18 feet), and a maximum wave height of 10.3 meters (34 feet) based in part on oceanographic survey data near the proposed terminal site.

Seasonal wave activity is summarized in Table 3-5 based on Brower et al. (1977). Several observers, including Sellman et al. (1972) and Wiseman et al. (1973), confirm the mild wave climate that predominates during summer, ice-free periods. Much more severe waves can occur under certain conditions, particularly during periods of pack ice retreat. Energy Interface Associates (1979) reports that, during some summers, the pack ice has retreated as far as 190 to 260 kilometers (120 to 160 miles) off the coast. Under these conditions, severe and rapidly moving storms proceeding across the shelf can generate waves over a long fetch. They report a shipboard observation of average wave heights on the order of 4 to 5 meters (13 to 17 feet) during a storm in the vicinity of Point Barrow in 1951.

3.2.1.6 Sea Ice

Expected ice conditions in the Barrow Arch planning area are briefly described based on several public and proprietary sources. Ice data for this area remains very limited. Ice data from ongoing and future surveillance projects should be used directly when they become available. Typical ice conditions in the northern Chukchi Sea are characterized by:

- o Ice coverage of close to 100 percent for most of the year
- o Dynamic pack ice conditions exist relative to those in the Beaufort Sea
- o Multi-year ice floes transported to the region from the Arctic
- o Ice decay and growth patterns that show distinctive climatological patterns related to bottom topography, proximity to warm water sources and a semi-permament ice circulation feature (Webster 1982).

Arctic Sea ice has a complex variety of forms, properties, and behaviors. Figure 3-3 illustrates the general extent of sea ice in the

TABLE 3-5

SEASONAL WAVE ACTIVITY FOR BARROW ARCH PLANNING AREA
PERCENT FREQUENCY OF OBSERVED WAVE HEIGHT THRESHOLDS
(NON-HAZARDOUS SEA CONDITIONS) IN CHUKCHI SEA (NORTH OF 70°N LATITUDE)

Wave Height

Month	Meters Feet	0 - 0.5 0 - 2	1 - 1.5 3 - 6	2 - 2.5 7 - 9	3 - 3.5 10 - 12	4 - 5.5 13 - 19	6 - 7.5 20 - 25
July		76%	21%	2%			
August		76%	21%	3%	1%		
September		61%	32%	5%	1%	1%	
October		67%	25%	1%			

Source: Brower et al. 1977.

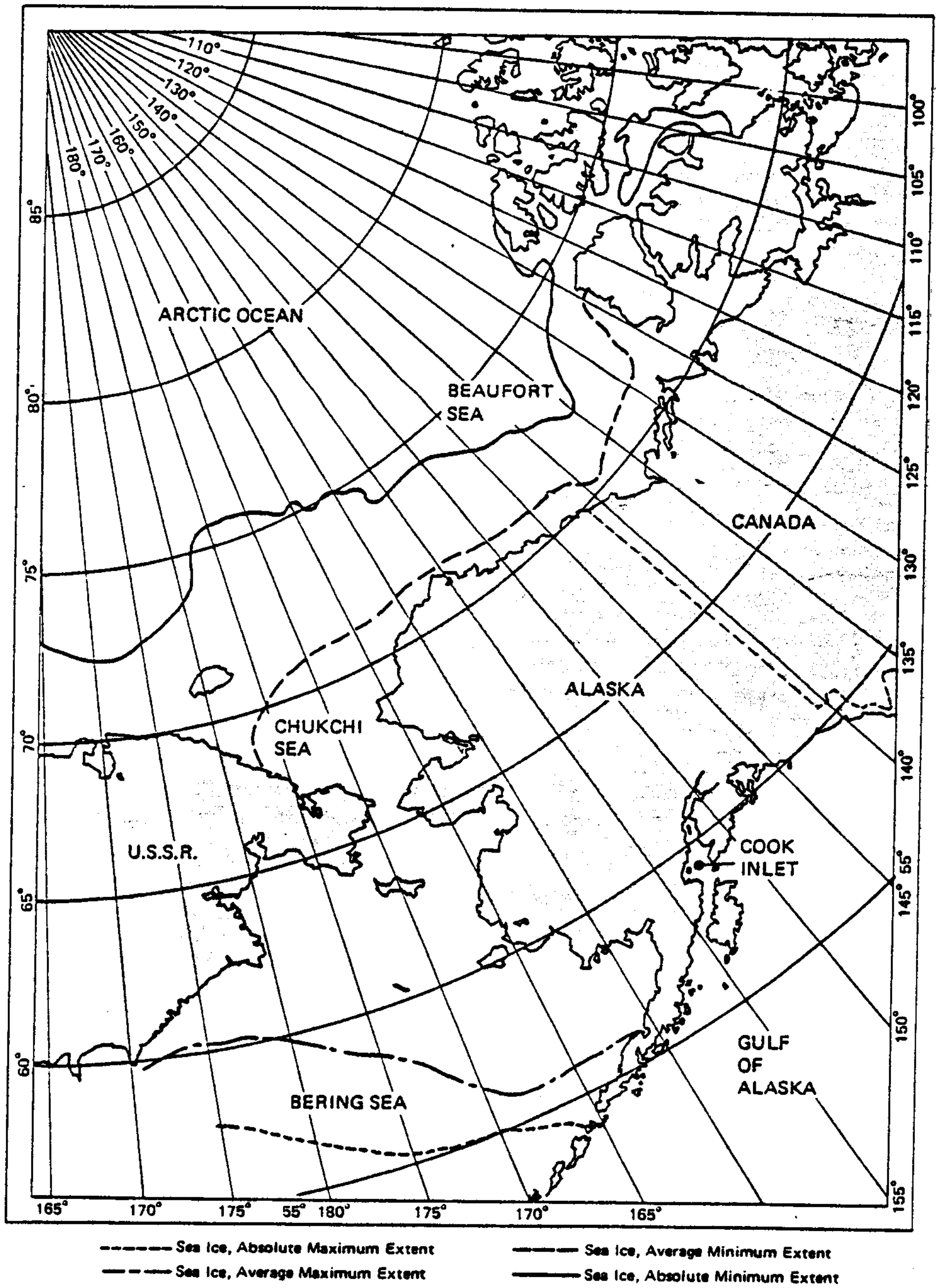


Figure 3-3

ALASKA ARCTIC SEAS & EXTENT OF SEA ICE

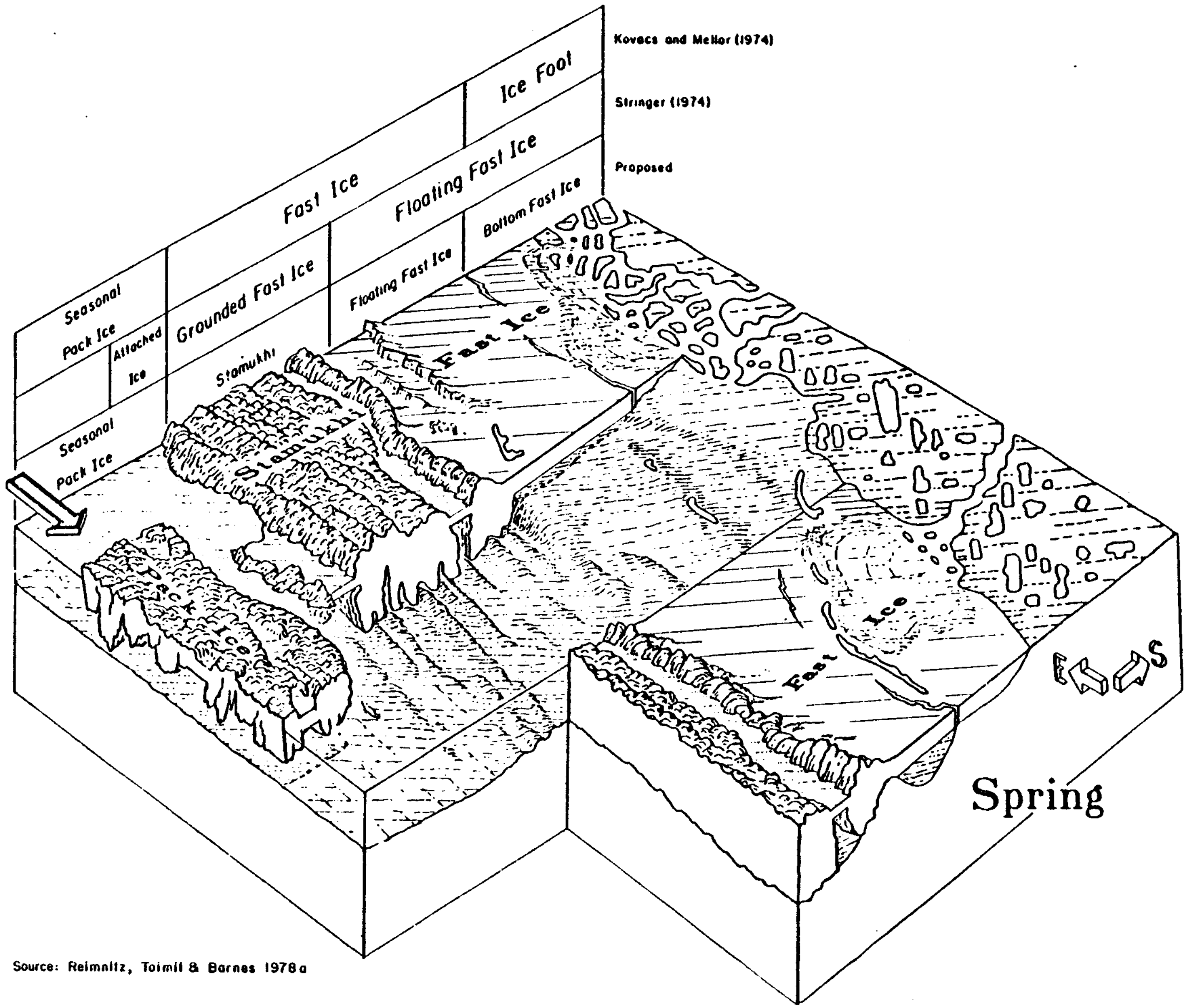
Source: National Academy of Sciences 1982

Alaskan arctic and Figures 3-4 and 3-5 illustrate the general patterns of spring and late winter ice zonation in the Arctic Ocean. In the Chukchi Sea, sea ice is year-round in waters north of 72°N and can be shifted at any time by winds and currents. The general ice movement is to the south through the Bering Strait under influences of wind and current (Ahlnas and Wender 1979; Reimer et al. 1981).

The Chukchi Sea remains virtually ice-covered for most of the year. From the beginning of December through May, 98 to 99 percent of the Chukchi Sea is covered with ice with the exception of a relatively wide shore lead that may develop seaward of the shore fast ice along the northwest coast (Webster 1982). From August to October ice coverage is least, but still averages 40 percent. First-year ice (fast ice and seasonal pack ice) forms 42 to 60 percent of the winter ice cover. Freeze-up generally begins by late September or early October and breakup occurs late the following June or early July. The first continuous fast-ice sheet is usually formed nearshore by mid to late October. This fast-ice sheet continues to extend and thicken throughout the winter. In general, stable land-fast ice is formed out to the 15-meter (50-foot) isobath by December, and out to the 30-meter (100-foot) isobath by March or April (Alaska Department of Fish and Game 1982).

North of Icy Cape, the fast ice freezes to thicknesses of 1.8 to 2.4 meters (6 to 8 feet). South of Icy Cape, the normal winter thickness is 0.6 to 1.2 meters (2 to 4 feet). The fast ice zone is generally most extensive between Cape Lisburne and Point Lay where shallow waters are extensive, and narrowest north of Icy Cape where bottom depth increases more rapidly and the shelf is vulnerable to pack ice incursion. The pack ice usually lies about 16 kilometers (10 miles) offshore from Icy Cape north toward Point Barrow. Beyond this point the edge of the pack ice swings northwest toward Wrangell Island. Pack ice intrusion is frequent along the coast as far south as Icy Cape (Alaska Department of Fish and Game 1982).

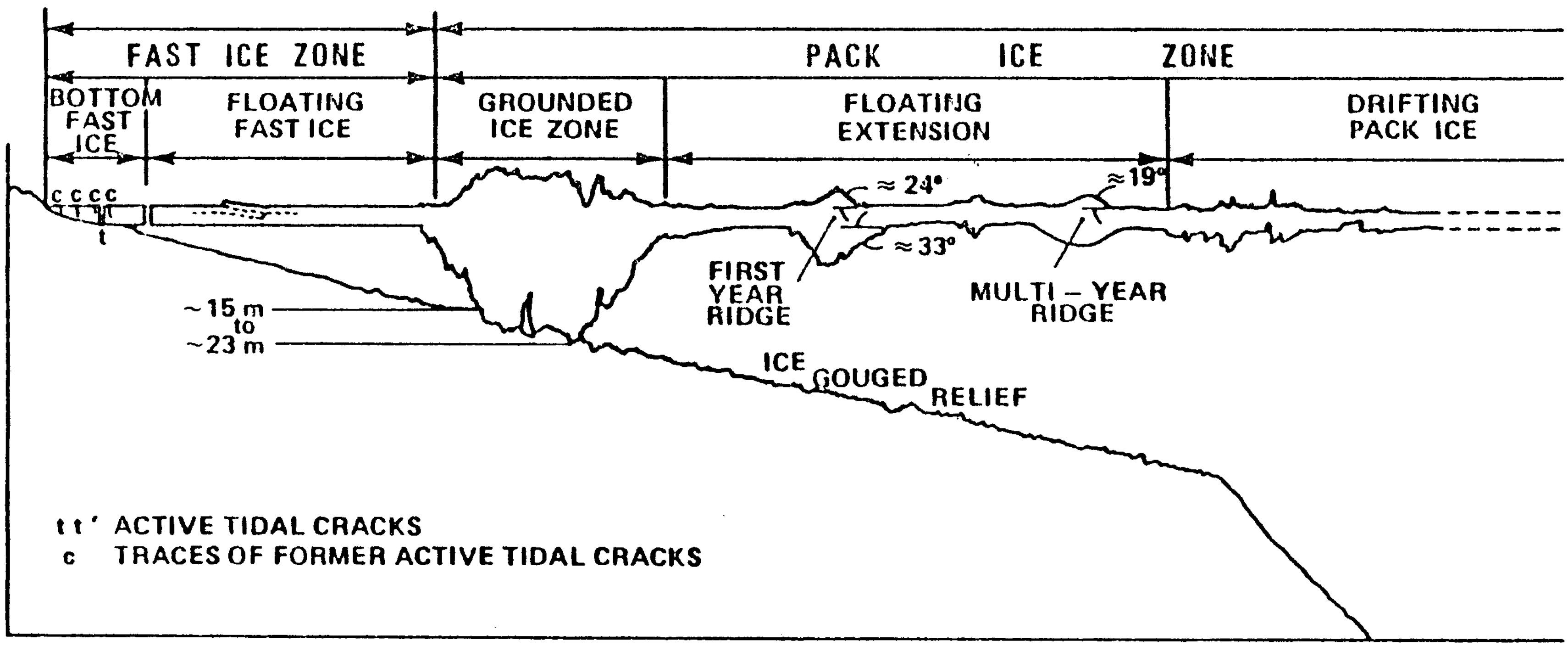
The multi-year pack ice lasts all year. Up to 40 percent of the ice cover between November and June may contain multi-year ice. Normally, polar pack ice is 3 to 4 meters (10 to 13 feet) thick at the end of winter and



Source: Reimnitz, Toimil & Barnes 1978a

Figure 3-4

SPRING ICE ZONATION OF THE ALASKA BEAUFORT SEA



Source: OCSEAP 1978

Figure 3-5

LATE WINTER ICE ZONATION OF THE ALASKA BEAUFORT SEA

decreases to 2 to 3 meters (6 to 10 feet) thick during the summer. In years of maximum ice retreat, the polar ice pack lies well north and west of the Chukchi Sea coast. The heavy pack ice begins to close in on the coast by October with new ice forming along its margin and in open-water areas between the pack ice and the shorefact ice. In heavy ice years, the pack ice lies close to the Chukchi coast and can unexpectedly be blown inshore even in midsummer. When it is blown ashore, ice keels, which can extend up to 20 meters (67 feet) deep, sometimes gouge into the sea floor (Alaska Department of Fish and Game). Ice islands with lateral dimensions of several kilometers are also known to occur (National Petroleum Council 1981).

During the winter and spring, the Chukchi Sea ice is more dynamic than Beaufort Sea ice. The Beaufort Sea has a large area of stable landfast ice often with an even larger area of immobile pack ice attached to it. Along the Chukchi coast there is an extremely active flaw zone lead system between the fast-ice and the moving pack ice. This lead system often extends from Point Barrow to Cape Lisburne and new ice in the flaw zone is continually being formed, detached, piled-up, and transported southward. In some years, the flaw zone may exceed 50 kilometers (30 miles) in width near its southern end (Burns, Shapiro and Fay 1981). The flaw zone becomes particularly pronounced from near Point Lay to Point Barrow during periods of strong easterly winds (Webster 1982).

Pack ice in the Chukchi Sea is continually in motion. Because of the southward converging Alaska and Siberian coastlines and the pressure exerted on the ice cover by the expanding polar ice pack, Chukchi Sea ice is heavily deformed. Another reason for this dynamic condition is the opportunity for ice in the Chukchi Sea to be transported southward out through the Bering Strait. Thicknesses of annual ice range from 100 to 120 centimeters (3 to 4 feet) with thicknesses of multi-year pack ice floes approaching 3 meters (10 feet; Webster 1982). Ridges can be several times this thickness.

Shear ridges or pressure ridges are formed where blocks of sea ice are slid, broken, pushed, and packed together. Pressure ridges are formed in the ice field due primarily to wind-induced stresses. There is at present very little data on the size, shape and distribution of ice ridges in the Chukchi Sea. The shear ridges generally have a sail height to keel depth ratio of 1:4.5, but this ratio can vary from 1:3 to as much as 1:9. Throughout the winter and early spring, ice movements create large and massive shear ridge systems. These shear ridges are most common along the shoals that extend seaward from capes and headlands. The ridging is particularly extensive in the nearshore area of the coast, north of Icy Cape and the offshore north of Cape Lisburne.

Pressure ridges are formed by compression of adjacent pack ice sheets when blocks of ice accumulate above and below the abutting ice floes. These pressure ridges may be free-floating or grounded if in shallow water. Both types of pressure ridges are frequent in the Chukchi Sea, and sail heights of 5 to 6 meters (18 to 20 feet) are found. In the northeastern Chukchi Sea, the frequency of pressure ridges is high, about 8 or 9 per kilometer (Kovacs and Weeks 1977). Average ridge thickness in February, including sail and keel is 9 meters (30 feet).

A probable range of ridge size and frequency has been extrapolated in Table 3-6 for the Barrow Arch planning area from some limited data assembled by the U.S. Army Corps of Engineers (1970), John J. McMullen Associates (1980), and Voelker et al. (1981). Pressure ridges can contain both first-year and multi-year ice. Based on a heat flow analysis, first-year ridges are estimated to have a consolidated zone thickness (i.e. with ice bonding) of less than 3.9 meters (13 feet). Multi-year pressure ridges probably can have a consolidated zone thickness exceeding 14 meters (45 feet) but the probability of encountering such a feature cannot yet be estimated.

Breakup in the Chukchi Sea occurs in late June or July. Commencing in late May or early June, river breakup causes estuarine flooding of the shorefast ice. Continued warming and summer insolation lead to melt pond formation on the ice by early June. The ice continues to decay and loosen its attachment to shore through June. Open water begins to form near river mouths and embayments. Eventually winds, storms, or water currents dislodge the fast ice, and breakup occurs usually in late June. This marks the

TABLE 3-6

EXTRAPOLATED PRESSURE RIDGE CHARACTERISTICS AND FREQUENCY

Sail Height (meters)	Sail Height (feet)	Keel Depth (meters)	Keel Depth (feet)	Number of Ridges per Kilometer
0.6 - 1.2	2 - 4	2.1 - 4.2	7 - 14	15
0.9 - 2.4	3 - 8	5.4 - 8.5	18 - 28	15
1.5 - 3.6	5 - 12	5.4 - 12.8	18 - 42	4
2.4 - 6.0	8 - 20	8.5 - 21.3	28 - 70	2
>6.0	>20	21.3	>70	2

Source: Brian Watt Associates

beginning of the "open-water season." Scattered leads open along the coast and the pack ice recedes offshore and begins its gradual disintegration.

It is not until the beginning of July that a significant reduction in probabilities of both the ice limit and 50 percent ice concentration boundary occurs in the southern Chukchi Sea (Webster 1982). As the ice decreases in concentration, it drifts north toward the Arctic Ocean. According to Webster (1982), the disintegrative influence on the ice cover is a tongue of warm water flowing northward through the Bering Strait. The probability of close pack ice falls to less than 50 percent south of Cape Lisburne and in a narrow corridor along the coast northeastward to Wainwright. This early lead formation is likely a result of a northeastward setting stream of warm water branching from a generally northward flow of water in the vicinity of Cape Lisburne referred to by Paquette and Bourke (1974) as the Alaska Coastal Current.

By the beginning of August, a narrow shore lead is likely to develop along the coast between Wainright and Barrow as the probabilities of encountering close pack ice fall to about 25 percent. However, there still remains a good chance that "heavy" ice concentrations will prevail in the area of Point Barrow and over the Chukchi Sea generally as far south as 71°N latitude. The lead increases in width through August. August and September are the months with least sea ice in the Chukchi Sea. These are the best months for navigation because the coastal area is generally free of fast ice to Point Barrow. The north-setting warm-water Alaska Coastal Current usually keeps the Chukchi coast free of ice through September. However, the presence of decaying ice fields still adhering to the shore along the Alaska northwest coast may complicate marine operations, including shore facilities. After September, freeze-up and the incursion of the pack ice prevent further vessel traffic, except for ice breakers.

A permanent circulation feature in the Arctic basin, which shunts ice westward north of the Alaska mainland and then northwestward between 155°W and 160°W longitude, maintains relatively high ice probabilities north of the mainland between Wainwright and Point Barrow throughout August and into

September. The withdrawal of the ice pack is greatest over the Chukchi Sea between 162° W and 175° W during this period. The persistence of sea ice west of 175° W seems largely due to the lack of any warm water inflow into the region to accelerate melting (Webster 1982).

The seasonal withdrawal of the ice pack from the Chukchi Sea exhibits, mainly in August, certain climatological configurations that have been related to current steering by bottom topography (Paquette and Bourke 1974). The literature associates these northward projections of lower ice probabilities with troughs in the sea floor that concentrate and direct the current into the marginal ice zone, thus creating bays of lower ice concentrations or open water. These features become less definable as the melt season progresses into September and the ice recedes farther northward over the continental shelf (Webster 1982).

The northward retreat of the ice pack peaks in mid-September when the median ice limit moves north of the Chukchi Sea to about 72° N latitude and the median edge of close pack ice recedes to near 73° N. The perennial polar pack in the Arctic Ocean begins its southward advance in late September. By mid-October, it is likely that sea ice will be found in the proximity of Barrow, but will likely be less than 50 percent concentrated, consisting mainly of new ice developing in situ. In extremely cold weather, new ice can develop in the coastal area as far south as Kotzebue Sound (Webster 1982).

After mid-October, sea ice forms more rapidly next to the cooling Alaska landmass than over the Chukchi Sea waters farther removed from the source of cold air. By November, sea ice will likely be extensive in the coastal waters from Cape Lisburne northward as well as in the interior of Kotzebue Sound. Farther westward the probabilities of the ice limit and 50 percent ice concentration boundary are lower with the contour pattern similar to that occurring during the ice melt-back period in August and September, presumably due to bathymetrically-induced current steering previously discussed. Freezeup is rapid during the first half of November and by the fifteenth it is likely that the waters north of the Bering Strait will be ice covered, becoming absolutely ice covered by December 1 (Webster 1982).

Ice conditions during the open-water season can vary considerably from year to year. Good ice years occur about 1 year in every 5. Exceptional ice years are less frequent (National Petroleum Council 1981). As mentioned earlier, the period of least ice cover is typically from mid-August to mid-October.

At most sites along the coast, the ice retreats some distance offshore during the summer. However, heavy pack ice and multi-year pack ice are never far away. Wind and currents can rapidly move the pack ice back onshore during summer months. Ice movements can be rapid. Pack ice is much more mobile than land-fast ice with movements of 10 to 20 kilometers (6 to 12 miles) per day being commonplace (Boone 1980). Shipboard observers passing through the Chukchi Sea have made anecdotal reports of ice movements estimated at up to 6 knots (Arctic Institute of North America, 1974).

In the Chukchi Sea, there is little data regarding ice movement except in the vicinity of Barrow. Several factors suggest that results of most Beaufort Sea ice studies are not directly applicable to the Chukchi. The Chukchi Sea has relatively few barrier islands to protect and stabilize the landfast ice sheet, except for the Kusegaluk Lagoon. Furthermore, the landfast ice zone is much narrower than in the Beaufort and is subject to considerably greater spring and winter pack ice movement (OCSEAP 1978). Other differences include a smaller inter-annual-fast ice variation along the Chukchi coast as well as a decrease in the intensity of ridging (OCSEAP 1978). However, the increasing activity in Beaufort Sea ice beyond the barrier islands will provide experience useful for Chukchi Sea development.

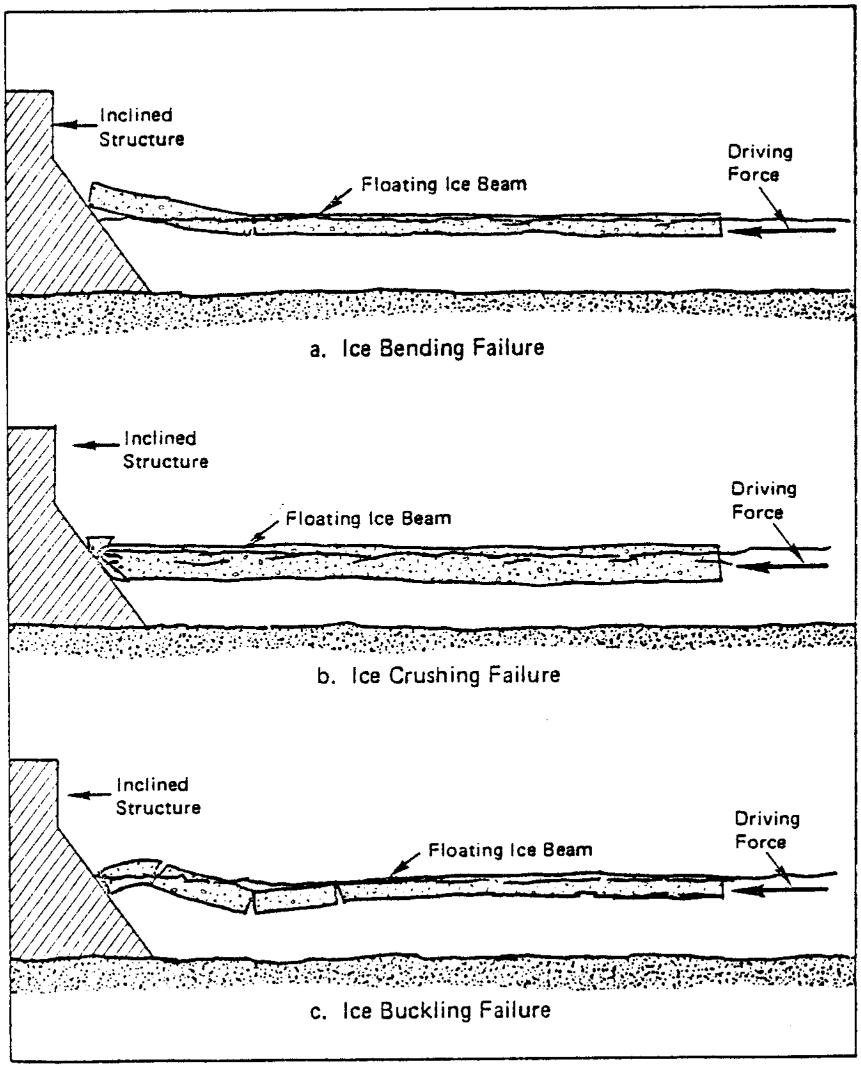
Stringer (1978), in addition to observing that the morphology of Chukchi Sea is considerably more dynamic than that in the Beaufort Sea, indicates that the two major ice features in the Chukchi Sea, the edge of contiguous pack ice and the location of large ridge systems, are relatively independent of each other. The former is controlled by season, being farther offshore during summer and advancing towards shore with advancing season, while the location of large ridge systems appears to be controlled mainly by bathymetric configurations.

In spite of those studies to measure ice movement, the statistical data base required for structural design is still limited. A larger data base consisting of measurements having both geographic and temporal continuity is required to estimate potential extremes. Any structure deployed in the open ice sheet for a period of years will be required to withstand many ice invasions. Continuing ice studies will be useful to provide adequate data for reliable prediction of expected ice forces, resulting in a safer design. By the time the first exploration structure is deployed in the Chukchi Sea, at least four more years of more detailed ice data will have been collected and analyzed. Prior to emplacing a production structure, at least eight years of more detailed ice data will be collected by industry operators.

Sea ice loads are a function of size and shape of the ice features, its strength and deformability and the mode of failure. Figure 3-6 illustrates three modes of ice failure. The strength of sea ice is a complex function of many factors including crystal type, strain rate, temperature, brine volume, and the direction of loading. The flexural strength of sea ice may be less than one-tenth of its compressive strength. This factor has a considerable influence on structure design (Watt 1982).

The design total ice forces will depend not only on the ice features but also on the structure configuration and contact surface characteristics. For the purposes of this planning study, Table 3-7 gives general ice loads suggested as examples for fixed structures to be located in the zone of large ice movement and where large multi-year ice features can be expected. In the (floating) landfast ice zone, ice movement will be significantly less and multi-year ice features will be less likely to be encountered. In this zone, a load of 350 kips per foot of waterline diameter for a vertical cylindrical structure or gravel island seems appropriate.

It is expected that engineering structures for the northern Chukchi Sea will have to be designed for very high and localized ice loads. Selecting appropriate design ice pressure criteria for these structures is a very



Source: National Academy of Sciences 1981

Figure 3-6

INTERACTION OF A FLOATING ICE BEAM WITH AN INCLINED STRUCTURE

TABLE 3-7

GENERALIZED ICE LOADS FOR REPRESENTATIVE DRILLING STRUCTURES IN DEEPER WATER[1]

Structure Type	Total Horizontal Load[2] (1000 kips)	Vertical Load (1000 kips)
Gravel Island	200[3]	0
Vertical Cylinder	140 - 200	0[4]
45° Cone	135 - 180	100 - 135
20° Cone	60 - 80	100 - 135

(1) See text for explanation.

(2) Total load includes both static (widely distributed) and impact (locally distributed) loads.

(3) For a 400-foot island, using 500 kips/foot of waterline diameter.

(4) Assumes no adfreeze plus tidal movement.

Source: Brian Watt Associates

difficult task due to the lack of data and industry experience. Bruen et al. (1981) discuss the complications involved in criteria selection and suggest a tentative relationship between the design ice pressure and the contact area under consideration. The suggested design ice pressure starts at 1600 psi for a 5 square foot area decreasing to 1200 psi for a 100 square foot area, and 500 psi for a 1000 square foot area.

3.2.2 Geology and Geologic Hazards

3.2.2.1 Major Data Sources and Reference Materials

The Chukchi Sea shelf, as a geographic and geologic unit, has received intermittent study from researchers over the last two decades, and a reasonable amount of knowledge has been accumulated about the structural, tectonic and environmental geology of the area. However, the Chukchi Sea has received considerably less attention than the Beaufort Sea, due to its remoteness from existing petroleum development and transportation infrastructure. Nevertheless, a limited amount of magnetic, gravity and seismic data is available, primarily from research conducted by the U.S. Geological Survey. At the time of this writing little of the available information had been synthesized, although a geohazards report is currently in preparation by the U.S. Geological Survey.

Further information and analysis of the geology of the Barrow Arch planning area are presented in Appendix A, emphasizing petroleum-related conditions.

3.2.2.2 Geologic Setting

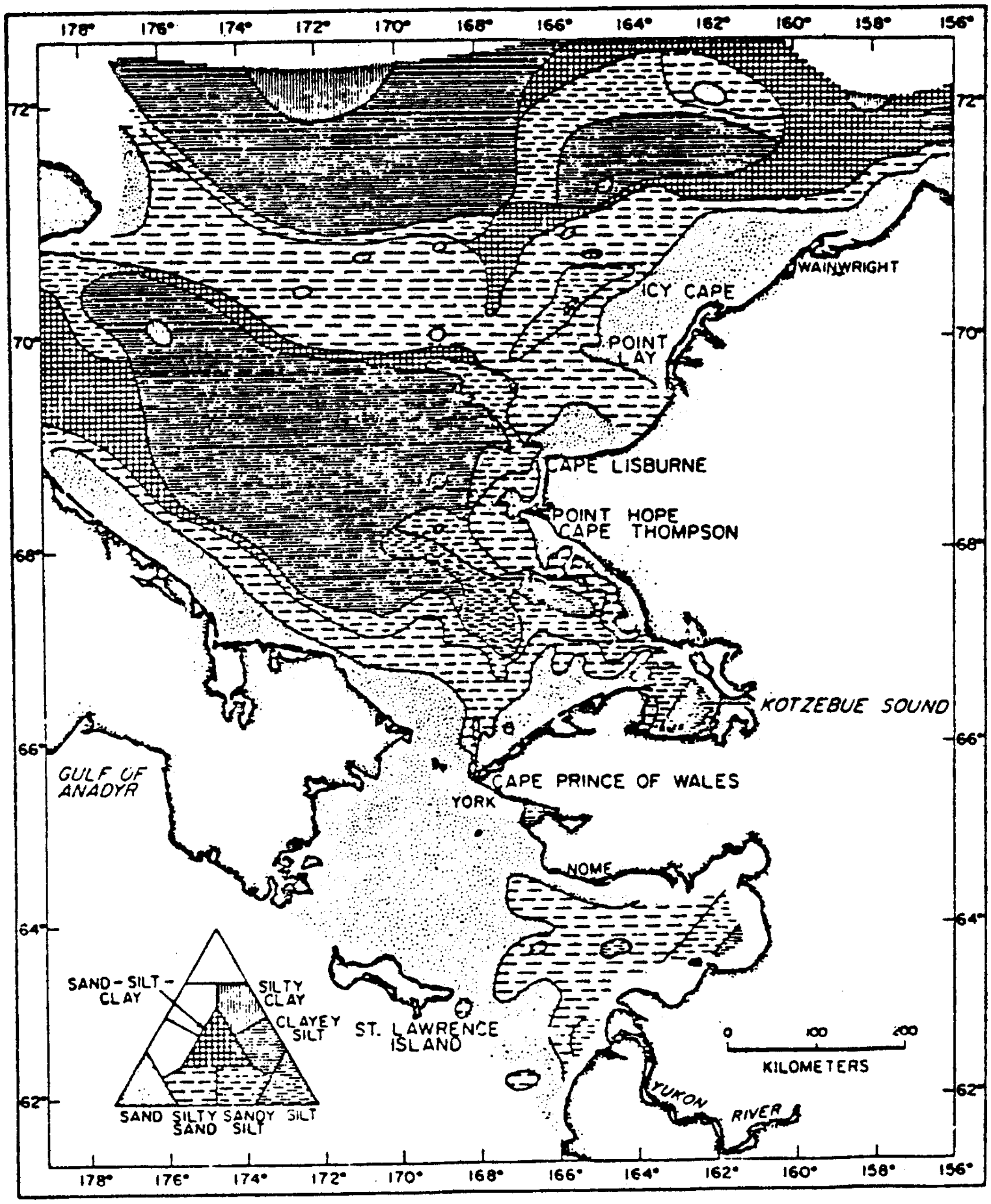
The Chukchi shelf is a peneplained, infolded sedimentary remnant. The extension of the Colville geosyncline beneath the Chukchi Sea shelf is comprised of lower Cretaceous and older sedimentary rocks with a presumed average thickness of 5 kilometers (3 miles) and a maximum thickness speculated at 8 kilometers (5 miles). It has been estimated that as much as

6,000 meters (20,000 feet) of Cretaceous sediments interbedded with volcanics may lie immediately offshore beneath the Chukchi Sea (Arctic Institute of North America 1974).

The thickness and stratigraphy of the pre-Cretaceous interval is in question. A great deal depends on the nature, age and extent of apparent basement highs indicated by gravity and magnetic surveys. Subottom reflections of the Tigara uplift area off Point Hope and Cape Lisburne indicate no stratification but suggest buried sedimentary rock. Basement rocks are generally believed to be complexly folded and faulted rocks of Devonian, Carboniferous, and early Mesozoic age (Moore 1964).

The sediment character of the Chukchi shelf is fairly well known, primarily from the work of Creager and McManus (1967). In general, the Chukchi shelf displays very low relief and is covered by thin relict and residual sediments with a minimal input of new fine sands, silt and clay from the Bering Strait and Kotzebue Sound (Ingham et al. 1972). Extreme diversity, even over short distances, is the most distinctive characteristic of arctic shelf sediments. The sediment cover rarely exceeds 10 meters (33 feet) and frequently is on the order of 3 to 5 meters (10 to 17 feet; Moore 1964). Sediments are predominantly overconsolidated Holocene silts and clays with widespread Pleistocene gravel sheets occurring at depths from 3 to 10 meters (10 to 33 feet; OCSEAP 1978). In water depths of 30 meters (100 feet) and more, bedrock is frequently exposed with only patches of sediment filling depressions (Moore 1964).

Bottom sediments in the area range from silt and clay through well-sorted sands to muddy or clean gravels. The bottom sediment characteristics of the Chukchi Sea, as described by Creager and McManus (1967), are illustrated in Figure 3-7. In general, grain size decreases away from the shore or downstream from the sediment source. Coarse gravel is almost always found near cliffs and headlands or with bedrock outcrops on the seafloor, except in the northeastern Chukchi Sea between Point Lay and Wainwright where gravel was noted offshore in relatively shallow water (Creager and McManus 1967).



Source Creager & McManus 1967

Figure 3-7

DISTRIBUTION OF BOTTOM SEDIMENTS, CHUKCHI SEA

In the nearshore waters of the Chukchi Sea and on the Chukchi shelf, sedimentary depositional structures are largely absent. A combination of ice bottom interaction and intensive bioturbation is considered the primary process, replacing older explanations that emphasized wave and current action (Barnes and Reimnitz 1974). Ice gouge phenomena are discussed in greater detail in Section 3.2.2.3.

Toimil and Grantz (1976) speculate that the anomalously coarse sediments reported on many shoals of the Chukchi shelf by Creager and McManus (1967) may in part result from seabed-sediment winnowing by processes related to repeated massive ice groundings or bergfields. They recognize, however, that the coarseness of sediments on some of the shoals can be more directly attributed to nearby outcrops or to wave and fluvial erosion and deposition during times of eustatically lowered sea level.

3.2.2.3 Geologic Hazards

Several types of potential geologic hazards to petroleum development exist in the proposed lease sale area. These include ice gouging, subsea permafrost, seismicity, and coastal erosion. Based on evidence reviewed for this report, volcanism and seafloor instability do not appear to be major risks in this region.

Sea ice reworks sediments and modifies bottom topography by impaction, plowing and gouging. Ice gouging or ice scour, as it is also called, may be caused by any type of ice with sufficient draft and momentum to penetrate the seafloor. Pressure ridges are probably the most common type of ice feature to produce major depressions in the seafloor although ice islands and their fragments are capable of scour as well. According to Barnes and Reimnitz (1974), ice processes appear to dominate the entire shelf of the Chukchi Sea, including the beach, during the winter season.

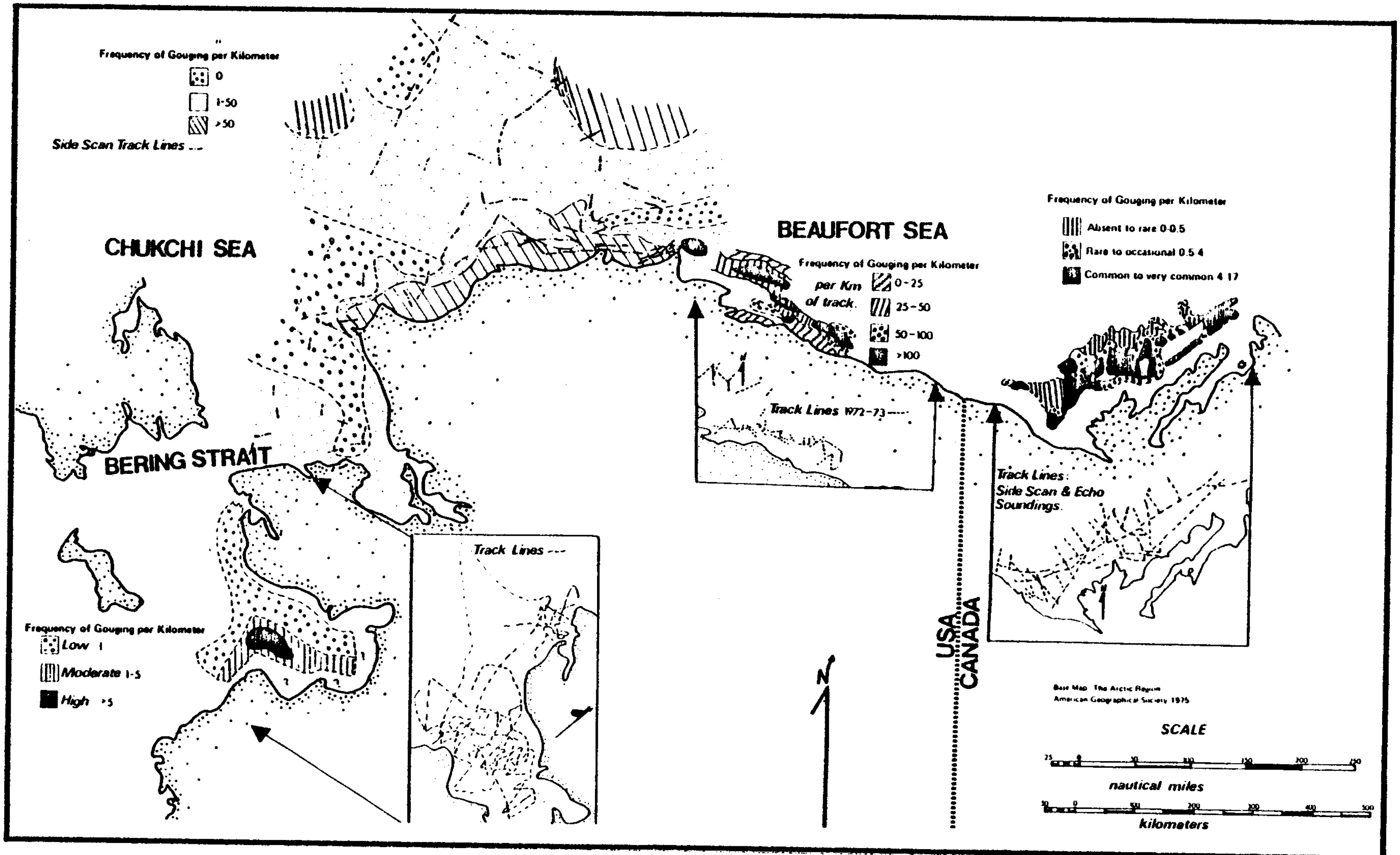
Reimnitz and Barnes' (1974) studies of the Beaufort Sea ice gouges indicate that ice-scoured relief tends to dominate the small-scale shelf morphology between depths of 8 to 10 meters (26 to 33 feet) and the greatest intensity of gouging corresponds to depths where the zone of grounded ridges (Stamukhi zone) is formed in 10 to 20 meters (33 to 66 feet) of water. Ice gouging is also especially intense on the seaward slopes of bathymetric highs. Figure 3-8 shows the location and density of see ice gouging in the Chukchi Sea (National Academy of Sciences 1982).

Toimil's (1979) reconnaissance study of ice scour in the eastern Chukchi Sea produced the following observations:

- The density of ice scour increases with increasing latitude, increasing slope gradients and decreasing water depth.
- Scour was observed to occur at least as far south as Cape Prince of Wales.
- Densities of over 200 gouges per kilometer (320 per mile) were encountered in water depths less than 30 meters (100 feet).
- No values higher than 50 per kilometer (80 per mile) were found in water depths deeper than 50 meters (165 feet).
- The maximum depth at which evidence of scour was observed was 58 meters (192 feet) and maximum incision (seafloor penetration) depths were found in water depths of 35 to 50 meters (115 to 165 feet).
- An extreme incision depth of 4.5 meters (15 feet) was encountered at a depth of 35 to 40 meters (115 to 130 feet).

Toimil (1979) also noted several differences between gouging in the Beaufort and Chukchi Seas:

- The maximum water depth of ice gouging occurrence appears to be shallower in the Chukchi Sea than the Beaufort Sea.



Source: National Academy of Sciences, 1982

Figure 3-8

DISTRIBUTION OF ICE GOUGES, OFFSHORE ALASKA

- In the Chukchi Sea, ice scour is associated with and may be modified by strong currents.

- Gouge trends in the Beaufort Sea are generally parallel to shore, reflecting the westward drift of pack ice, but this feature is poorly developed in the Chukchi Sea.

- In the Chukchi sea, gouge densities are variable and patchy under otherwise uniform conditions.

In spite of a fairly limited data base, several characteristics of the region's seismicity are known. In general most parts of the arctic coastal plain and the Chukchi Sea are characterized by low seismicity. The only reported seismic activity with a Richter magnitude greater than 6.0 occurred in the Hope Basin portion of the southern Chukchi Sea where four epicenters have been recorded in the last 30 years (Eittreim and Grantz 1977). According to the American Petroleum Institute (1982b), the Barrow Arch planning area falls into earthquake zone 1.

Although ice-bonded permafrost is known to be widely distributed on the Beaufort Sea shelf, little is known about conditions on the Chukchi shelf (Weeks et al. 1978). The Arctic Institute of North America (1974) indicates that while relict permafrost is known to occur beneath the coastal waters of the Chukchi Sea, little is known about its areal distribution, thickness, nature and equilibrium conditions.

According to Barnes and Hopkins (1978), subsea relict permafrost is most likely to be encountered in shallow, inshore areas where ice rests directly on the seabed. Relict permafrost may be encountered on any part of the shelf inshore of the 90-meter (300-foot) isobath. Larry Phillips (personal communication, 1982) of the U.S. Geological Survey in Menlo Park, California indicates that subsea permafrost is unlikely to be found extensively offshore due to the thickness of Holocene sediments. While several OCSEAP investigators continue to study the pattern of subsea permafrost occurrence on the Chukchi Sea shelf, no more recent data is available.

Frozen gas hydrates or clathrates are a geological feature often encountered in association with or below ice-bonded permafrost zones. They occur as a latticework of gas and water molecules with a typical ratio of one gas molecule to six water molecules (Energy Interface Associates 1979). When heated, clathrates may decompose, releasing gas with a much greater volume and/or pressure than it had in the frozen state. Because of the high pressures that may accompany thawing, frozen hydrates are of concern to offshore drilling operations in arctic waters.

Little is known about the distribution of clathrates on the Chukchi Sea shelf. Indirect evidence from seismic reflection records indicates that clathrates may be widespread in the Beaufort Sea (Weeks et al. 1978).

The coast along the Chukchi Sea is generally a narrow transition zone between the tundra surface and the sea (Arctic Institute of North America 1974). It ranges from steep, nearly continuous sea cliffs with gullies and narrow valleys to low, gentle slopes where the sea meets the plain with little discernible shoreline break. The nearshore regime is composed of both semi-enclosed lagoons and open embayments with common coastal landform features such as beaches, barrier islands, barrier bars, spits, dunes and river deltas. During the short summer when sea ice moves off the coast, thermal and wave erosion form steep sea cliffs, and a marked annual retreat of shorelines occurs.

Studies of coastal erosion in the Barrow region show that annual rates of cliff retreat east of Barrow in Elson Lagoon generally exceed 1 meter/year (3.5 feet/year) and occasionally exceed 10 meters/year (33 feet/year; Harper 1978). However, west of Barrow along the Chukchi Sea coast, cliff erosion rates have been measured at 0.3 to 3 meters/year (1 to 10 feet/year) with a long-term retreat rate of over 2 meters/year (7 feet/year; Harper 1978).

Harper (1978) speculates that temporal variations in erosion rates may result from variations in annual wave energy levels associated with storms, migratory bar-attachment points, and localized beach borrow activity.

An additional concern affecting not only coastal erosion rates but also the siting of onshore support facilities is ice pile-up or ride-up events. Described by Kovacs and Weeks (1981), shore ice pile-up and override are frequent events along arctic shorelines. Events generally occur between March and June in the Chukchi Sea. Ice override events can affect structures up to 25 meters (80 feet) from the waterline at elevations of 6 meters (20 feet), even within barrier islands. Shore ice pile-ups along the Chukchi Sea coast in 1981 were found to be massive, some reaching heights of 20 meters (66 feet) and extending continuously along several kilometers of shoreline. Ice override events of more than 30 years ago produced inland ice movements of at least 125 meters (410 feet) near Camden Bay in the Beaufort Sea (Kovacs and Kovacs 1982). Ice pile-up events can also produce extensive soil berms and tundra scars.

A final geologic hazard, overpressured shales possibly occurring in the northern Chukchi Sea basin, may pose drilling problems. These shales are associated with upthrusting shale diapirs areas and may cause well control problems when encountering fluid pockets. See Appendix A for further discussion.

3.2.3 Biology

The Barrow Arch planning area is characterized by significant seasonal and year-round populations of mammals, birds and fish. The area has year-round populations of marine mammals including ringed seals and bearded seals. Polar bears are also found on pack ice and occasionally den in the area from Point Hope to the Kuparuk River. Some barren-ground caribou overwinter in the Icy Cape to Point Lay area. Seasonal populations of bowhead whales, belukha whales, spotted seals, walruses and gray whales are common. Some 13 other species of marine mammals are occasional or rare inhabitants of the region. The endangered bowheads migrate in the ice leads in the northern Chukchi Sea in April and May, and return westward in the fall. Bowheads have been sighted off Barrow as late as November. Walruses use the pack ice edge of the northern Chukchi Sea as summer habitat, migrating in spring and fall within several miles of shore and feeding in mollusk beds (Arctic Institute of North America 1974).

Sea bird colonies are of minor importance in the area north of Cape Lisburne. The northernmost nesting sea bird colony in the Arctic is located at Cape Beaufort. Birds are transient in the northern Chukchi Sea. Sea birds are seasonally present from May through September. The largest concentrations are found in coastal areas between July and September. Large late summer concentrations are found at Peard Bay and on Solovik Island near Icy Cape. Nesting seabird colonies are found at Capes Thompson and Lisburne and in Kotzebue Sound. The endangered arctic peregrine falcon is found between Cape Lisburne and Point Lay (Arctic Institute of North America 1974).

In the Chukchi Sea, waterfowl make extensive use of shore leads in May. Significant year-to-year variations exist in habitat use by post-breeding migrants, making delineation of critical habitat difficult. Potential OCS development conflicts with birds include use of open ice leads by barge and tanker traffic, aircraft overflights and onshore support facilities. Major bird nesting colonies are located south of Cape Beaufort (OCSEAP 1978). Regulatory measures exist to mitigate potential OCS conflicts with birds according to their demonstrated significance and long term impact.

The majority of the fish found in the Chukchi Sea area fall into one of five species: arctic cod, arctic cisco, least cisco, arctic char, and fourhorn sculpin. The arctic cod is the major secondary consumer in the arctic marine food chain. A few small commercial salmon runs are present in Kotzebue Sound (Arctic Institute of North America 1974). The major potential conflict with fish concerns possible disturbance of fish overwintering areas under ice. This conflict is most likely to occur in connection with any winter gravel dredging from fresh water lakes or rivers in the area. In general, potential conflicts with fish are likely to be limited to the construction and operation of shore base and marine terminal facilities discussed in Chapter 4.0.

Arctic ecosystems display considerable resilience, effectively coping with extremes of temperature, light and salinity, and inconstancy in ice cover and length of the growing season. However, sensitivities to disturbance do exist. Arctic species are generally long-lived and slow to reproduce. Disturbed communities may repopulate, but over a relatively long time period as recruitment rates are generally low (OCSEAP 1978).

Considering the above the major biological concerns related to Chukchi Sea OCS development will b: the endangered species (principally the Bowhead whale) and native subsist nce issues (including the Bowhead, other marine mammals, polar bears anc food fishes). Future lease stipulations and mitigation measures may be expected to affect how the arctic oil development activities proceed, especially during the limited and intense open water season (see assumptions in this study regarding impact of regulations, discussed in sections 1.2, 4.5 and 6.3).

3.3 Field Development Components

The presence of sea ice in Chukchi Sea waters poses a serious challenge in the design of offshore field development components for the exploration and production of oil and gas. Water depth is also an important factor, but present technological capabilities for arctic areas are on a different scale from those for ice-free OCS areas. Water depths from 3 to 60 meters (10 to 200 feet) are found across the relatively shallow Chukchi Sea shelf. Due to industry's relatively limited experience in open-coast sea ice environments, the term "deep water" may be appropriate for arctic water depths beyond 30 meters (100 feet).

The progressively more severe ice conditions found as one moves north in the Chukchi Sea substantially limits the summer season during which conventional open-water drilling and construction techniques can be used. Ice-designed vessels and operations plans can somewhat extend the drilling/construction season for floating equipment. This limitation is such that only bottom-founded, ice-resistant concepts have been seriously considered as first-generation technologies for year-round exploration drilling and oil field development in the Chukchi Sea.

Statistically, there is only a 35 percent chance of the working time in any year being as great as the mean open water period. Thus considerable potential for a short work season exists in planning and costing offshore operations in the Arctic; it is unreasonable to assume that something close to the mean open-water period will be available for summertime construction (Jahns 1980).

All structures emplaced in the multi-year pack ice zone will have to be capable of resisting the dynamic forces developed by moving ice. Beyond the landfast ice zone, multiple ridges form in the shear zone of transition between the stationary ice and the moving multi-year ice of the polar gyre. Exploration and production systems will have to deploy slope protection systems or employ passive design concepts to survive in the shear zone and the multi-year ice beyond. Bottom-founded systems must be flexible enough to absorb the initial concentrated loading from large irregular ice shapes while spreading the load over a large enough area to mobilize the concept's mass resistance and thus develop the forces required to cause failure of the largest ice features (Downie and Coulter 1980).

Weather will also play a role in affecting exploration programs. Limited visibility due to fog and snow can occur anytime, and is most prevalent in the open-water season. High wind and waves, particularly those associated with early fall storms may shorten exploration seasons or affect the construction period for exploration concepts such as artificial islands. Any year-round exploration operations may also be adversely affected by the severe cold of winter and the limited visibility due to fog and snow.

The remoteness of the Barrow Arch planning area from developed ports and industrial centers and its lack of in-place shore facilities capable of supporting an exploration program is another constraint. The great supply distances will make crew rotations and resupply more difficult and costly. Crew rotations and critical spares will be transported by air. An airstrip and forward base along the northern coast, probably in the vicinity of Wainwright seems probable although temporary facilities could just as easily be established in close proximity to the exploration effort. Resupply of bulky materials such as mud and water and any material required for construction or emplacement of exploration platforms will probably be barged from an expanded regional supply center such as Nome or Kotzebue. Desalination units might be installed for water supply.

It should be emphasized that any of the concepts to be employed for exploration of the Chukchi Sea will be considerably more expensive than similar equipment for sub-arctic or non-arctic OCS regions. Compounding this problem is the fact that at present, little purpose-built equipment for operation in arctic regions is available. While some conventional equipment can be employed on a seasonal basis, the requirement for ice-survivable platform concepts and supporting equipment implies considerable costs for design and construction of new equipment. Therefore, exploration programs will have to be carefully planned and executed with maximum opportunities for cost-savings realized. Also, due to the high costs of developing fields in offshore basins with severe ice conditions, more exploratory delineation drilling than is normal may be required to evaluate the production potential of a prospect.

3.3.1.1 Exploration Platforms Selected for Representative Water Depths

Based on a review of the Barrow Arch planning area's petroleum geology and bathymetry, two representative water depths were selected as the basis on which to select suitable exploration concepts. The selected water depths are 15 meters (50 feet) and 37 meters (120 feet). Two additional water depths, 27 meters (90 feet) and 60 meters (200 feet) were examined less rigorously.

The shallower depth occurs only over a limited area of the federal waters just beyond the State of Alaska (3-mile) jurisdiction zone. This coastal strip of seafloor is most likely to contain extensions of geologic structures characteristic of the prolific North Slope.

The 37-meter (120-foot) depth was selected because it is most typical for significant areas of the relatively level central Chukchi shelf. The other two depths were briefly examined for transitional (limited area) and extreme (deepest with any reasonable interest) cases.

The following are the exploration concepts appropriate to each selected water depth for the Chukchi Sea:

15 meters (50 feet)

- Artificial gravel fill drilling island -- "gravel island"(1)
- Caisson-retained gravel drilling island

27 meters (90 feet)

- Caisson-retained gravel drilling island
- Conical drilling unit

37 meters (120 feet)

- Caisson-retained gravel drilling island
- Mobile caisson rig
- Conical drilling unit, other ice-strengthened floating platform

60 meters (200 feet)

- Conical drilling unit/round drillship
- Ice-reinforced semi-submersible, drillship and turret-moored drillship
- Mobile caisson rig

(1) The widely used term "gravel island" is used generally in this report to refer to any type of artificial island or underwater berm for structural foundation support constructed from fill materials that can have a wide range of grain sizes.

3.3.1.2 Construction, Transportation and Installation Techniques for Selected Exploration Concepts

At the selected shallow water depth of 15 meters (50 feet), several exploration concepts seem feasible. The most viable technologies for extending the exploration drilling period beyond the open-water season are artificial islands. Artificial islands are suitable for operations in water depths out to 18 meters (60 feet) and several Canadian operators are experimenting with island-building techniques for 20- to 60-meter (65- to 200-foot) water depths (Ocean Industry 1982).

The cost of constructing an artificial island is very sensitive to the availability of fill material, the type of fill material used, the location and depth of the fill material and the method of island construction. Experience has shown that only free-draining materials such as gravel or sands with an average grain size of 150 microns or greater and with less than 10 percent silt are acceptable as building materials (de Jong and Bruce 1978).

For the Barrow Arch planning area, two major types of artificial islands appear most likely for exploration purposes. They are:

- o Gravel islands
- o Caisson-retained gravel islands.

Man-made islands of gravel or other dredge fill offer the distinct advantage that drilling can be conducted in essentially the same manner as on land. They can be designed for year-round operations. Islands are gravity structures that resist lateral ice loads by their large weight. By adjusting the island size and freeboard, the sliding resistance on the sea floor or on any given shear plane through the island fill can be adjusted as necessary to assure a stable platform for the anticipated ice loading conditions (Jahns 1980). Thus, this type of structure can be easily adapted to site-specific design parameters. Also, temporary islands for exploration drilling can be enlarged and transformed into a permanent production platform if a discovery is made. Gravel islands have been found to have minimal impacts on the environment at their location, both during construction and after the islands have been completed (Wright 1977). Once abandoned, they disappear gradually due to natural erosion.

The design of artificial islands requires a consideration of ice forces, storm waves and tides, geotechnical and seismic properties of the seabed, and availability and engineering characteristics of the fill material. Three techniques are available for the construction of gravel or other fill-based artificial islands. They are:

- o Dredging of gravel from on-site seabed sources during open-water season.
- o Dredging of gravel from off-site seabed sources and barging on-site during open-water season.
- o Dredging of gravel from onshore borrow sources and winter transport over ice roads to the offshore site and island construction through a hole in the ice.

Due to the ice conditions at the selected water depths in the Chukchi Sea, only the first two techniques are feasible. The technique of over-ice winter construction utilized in the Beaufort Sea will not be possible since island construction will take place beyond the boundary of the smooth and stationary land-fast ice zone over which ice roads can be constructed.

Since only open-water construction techniques can be used in the Chukchi Sea to emplace artificial islands, scheduling constraints, weather, and ice conditions all become critical elements in successful island completion. The availability of suitable gravel fill material is critical for selecting island sites. Gravel is the preferred fill material since it offers faster consolidation, steeper stable slopes, and better resistance to wave or ice erosion of the constructed island. For purposes of this study, we have assumed that sufficient gravel deposits to construct any artificial island concept are located within a reasonable distance of the site.

Exploratory Gravel Fill Drilling Island

Given a sufficient supply of granular borrow material in the vicinity of a proposed island site, a gravel island can be constructed for exploration drilling. Prior to initiating dredging, an extensive borrow research program is conducted employing coring, high resolution seismic data and dredge tests. Once suitable borrow pits are identified, dredge equipment can be employed. Table 3-8 shows an example construction spread for construction of an exploratory gravel island. Figure 3-9 shows an elevation of an arctic exploratory drilling island constructed entirely of fill materials. It depicts side slopes of 1:15, while the island designs developed by SF/Braun for use in the economic analysis have side slopes of 1:10. A representative island will be designed with a circular working surface of 100 meters (330 feet) across, large enough to accommodate an arctic drilling rig, drilling supplies and fuel tanks. Design geometry is selected to protect against wave and ice attack and is based on expected fill properties. Standard design practice is to establish freeboard height as a function of intended platform life coupled with the probability of encountering an extreme wave and storm tide height (Energy Interface Associates 1979).

The rapid rate of island construction (up to 2,000 cubic meters [2,200 cubic yards] per hour) required by the short open-water season and the magnitude of the fill requirements necessitates controlled distribution of material over the site to reduce the risk of slope failure (Boone 1980). It is not possible to accurately predict losses due to erosion during construction. This depends greatly on weather conditions. Enough experience has been obtained with all-fill islands constructed to date to indicate that this is a serious problem. A particular problem is the building up of the island through the wave zone.

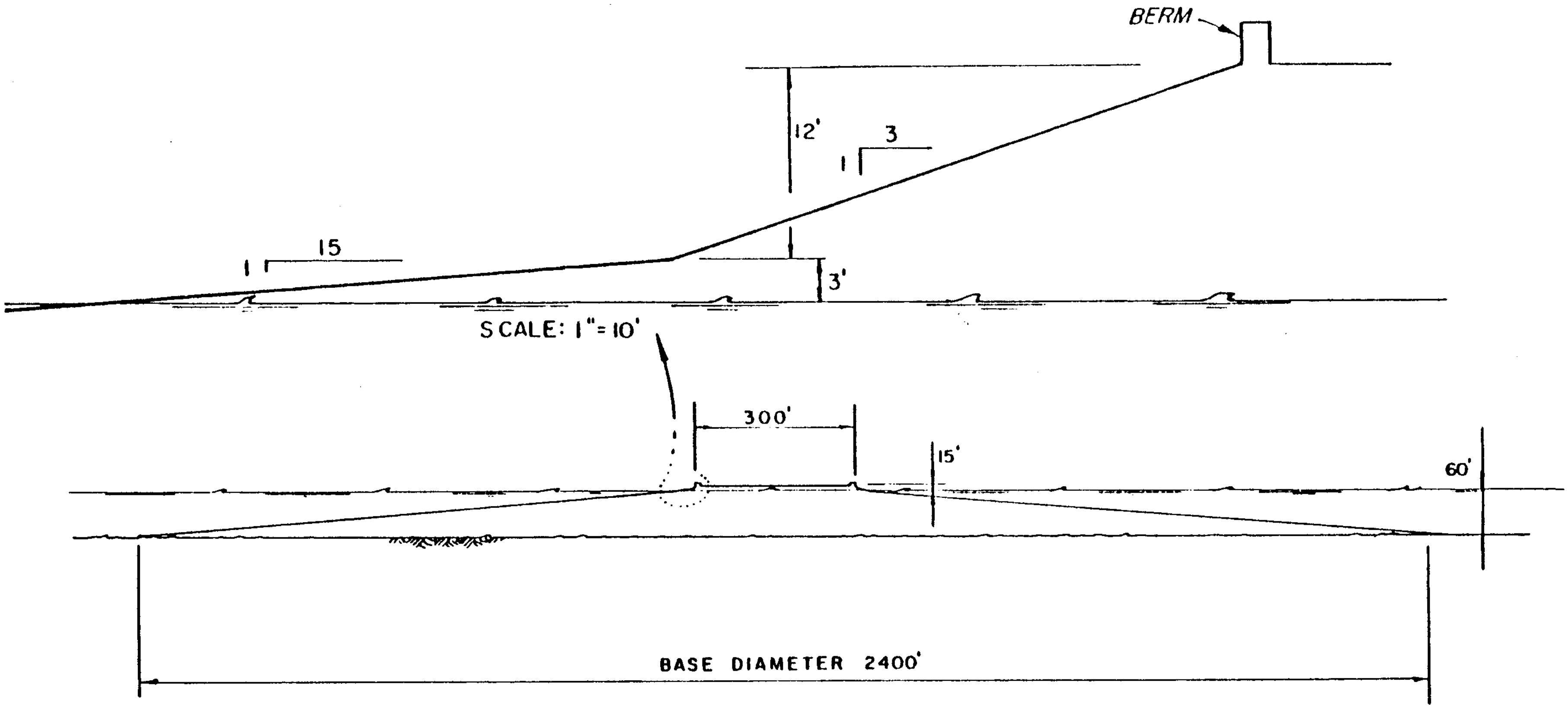
TABLE 3-8

EQUIPMENT SPREAD FOR CONSTRUCTION OF A GRAVEL ISLAND
IN 15-METER (50-FOOT) WATER DEPTH*

- 3 cutter head suction dredges
- 4 barges
- 2 derrick barges
- 12 work boats (tugs, survey vessels, etc.)
- 2 Icebreakers
- 2 Quarters Barges (worker accommodations)
- 2 Caterpillar tractors

* Assumes availability of gravel sources within direct dredge pumping distance -- on the order of one kilometer, and that the open-water construction season is short -- about 70 days.

Source: SF/Braun



Source: National Petroleum Council 1981

Figure 3-9

ELEVATION OF ARCTIC EXPLORATORY DRILLING ISLAND

A key consideration in successful island construction is availability on site of enough dredging power to produce the required fill material within the time allowed for construction. Trailer suction hopper dredges offer distinct advantages over stationary suction dredges because of their ability to work in sea states with up to 3-meter (10-foot) waves and 65-kilometer (40-mile) per hour winds along with rapid mobilization after a shutdown due to storms. In addition to several trailing suction hopper dredges of approximately 6,500-cubic meter (8,500-cubic yard) capacity, a stationary suction dredger/crane/work barge with a large crane mounted is preferred to build up the island or base berm from a stockpile deposited adjacent to the island site by the trailing suction hopper dredgers. If open-water season weather conditions permit, an alternative technique is use of a pontoon floating pipe to move the stockpile onto the island site. The same stationary suction dredger with mounted crane can be used to overbuild the sacrificial beach to provide for maintenance requirements. The same unit can also provide the lifting capacity for many miscellaneous tasks and the location of a floating construction camp at the island site (Downie and Coulter 1980).

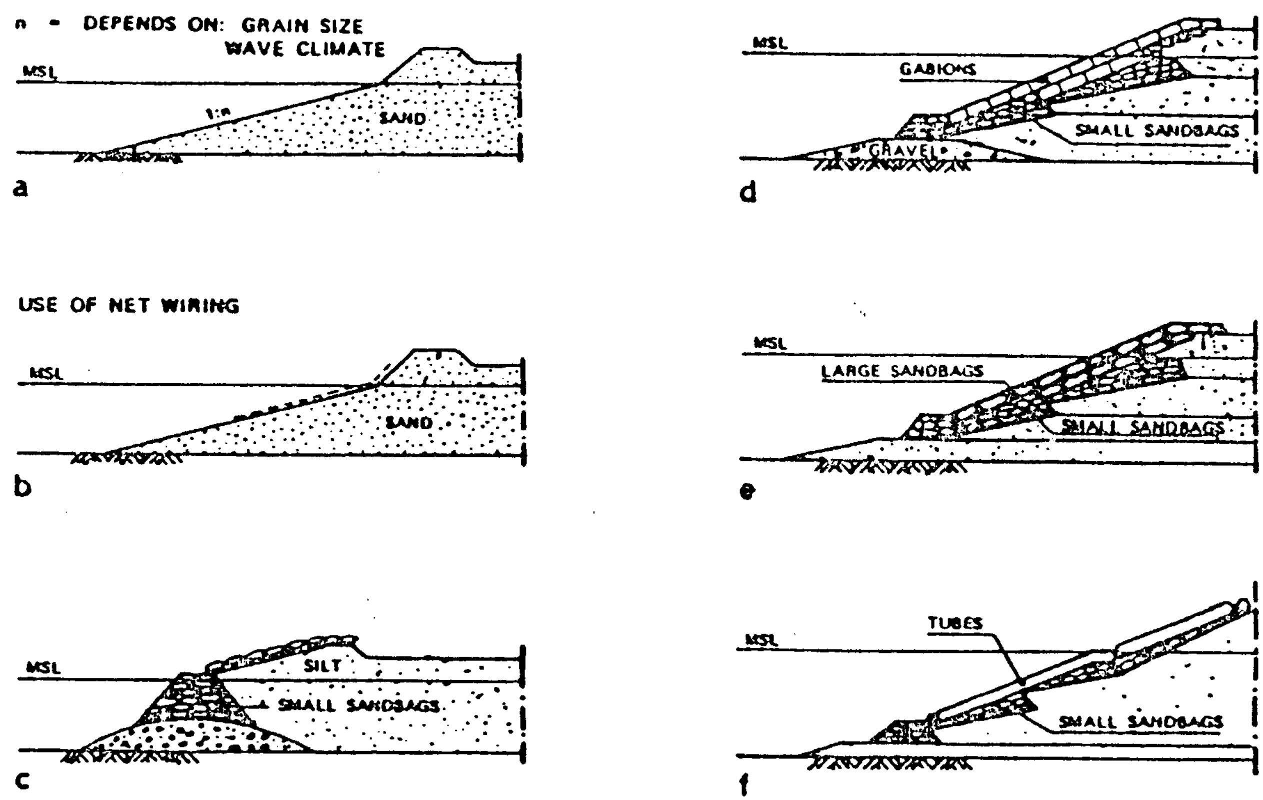
In its construction of the Issungnak sand island in 20 meters (66 feet) in 1978-1979 in the Canadian Beaufort Sea, Esso Resources Canada (formerly Imperial Oil Ltd.) used two stationary suction dredges to move fill from borrow pits on site. One dredge, the Beaver Mackenzie, provided the backbone of the fill movement with its 70,000-cubic meter (90,000-cubic yard) per day capacity. One smaller cutter suction dredge was employed to fill 1500-cubic meter [2,000-cubic yard) capacity split-bottom dump barges with sand from a remote borrow site. The dump barges stockpiled this material at the island site for use in completing the island. Floating pipelines with alternating rubber and steel pipe sections were used. Several pipeline breaks did take place without significantly disrupting operations. Average dredge production over a 69-day ice-free season was 23,400 cubic meters (30,600 cubic yards) per day (Boone 1980).

Marine support at the Issungnak construction site was enhanced by use of a 60-man camp onboard an ice-strengthened accomodation barge. This improved communication, allowed faster response time to potential problems and reduced dependence on weather. There is also a need for sheltered water in the vicinity of an island construction site. Dredging of a small harbor for tugs, supply barges and other vessels may be required. If more than one open-water construction season is required for island construction, ice-strengthened dredges and other vessels may be overwintered in harborage dredged behind nearshore barrier islands.

A critical point in island construction is reached at the end of the construction season where the island breaks the water surface and is topped off. According to Boone (1980), a period of relatively calm water at the end of the construction season is required for this final step. Imperial's Issungnak island nearly floundered at this point due to erosion caused by overtopping waves. In fact, the completed 4.1 million-cubic meter (5.3 million-cubic yard) island had a final freeboard of only 1.5 meters (5 feet) instead of the 5-meter (16-foot) design freeboard due to the erosion. Nevertheless, despite problems associated with moving equipment on and off the surface of islands, and preventing dredge pipe damage in breaking waves, the island was completed and a winter exploratory well successfully drilled.

Hydraulic fill exploratory islands are generally fortified with one of a number of slope protection features to provide short-term protection against wave and ice erosion of the island's sacrificial beach. These may be rocks, gabions, sand bags, wire netting, concrete mats, or some combination of these. Figure 3-10 illustrates several types of shore protection features. Slope protection devices will be installed by a derrick barge once an island's basic form is completed. It may also be necessary to add a dock by creating an arm or shoulder of fill on the island to provide berth space to land heavy equipment and to emplace the exploratory drilling rig.

Artificial islands at shallower water depths have significant advantages over conventional drilling platforms designed for arctic conditions. The key is use of equipment with sufficient dredging capacity to complete the island in the time allowed for construction. According to SF/Braun,



Source: de Jong 1975

Figure 3-10

GENERAL DESIGN OF SHORE PROTECTION FOR ARTIFICIAL ISLANDS

artificial islands out to 15-meter (50-foot) water depths can probably be constructed in one season, although annual variations in open-water seasons or equipment failures could force multi-year construction.

Exploratory Caisson-Retained Gravel Island

As exploration moves to deeper waters and to areas where sand or gravel is not available, simple dredge fill islands become very expensive. According to the Oil and Gas Journal (1981), as water depth doubles, the volume of fill needed to construct hydraulic fill islands quadruples. While industry is experimenting with construction of islands with steeper slopes to minimize fill requirements, other artificial island concepts offer significant advantages over all-fill concepts.

The caisson-retained concept was developed to reduce costs by reducing fill requirements, simplifying construction methods and eliminating the need for elaborate slope protection. It also offers several other advantages over all-gravel artificial islands. The steeper side slopes make it easier to maneuver barges or other vessels in close, facilitating lifts of equipment. Caisson-retained islands also offer a potential for reusability, since the caisson might be removed and floated onto another site. Table 3-9 illustrates the reduced fill requirements of a caisson retained island at several different water depths as compared to two types of all-fill artificial island construction. Figures 3-11, 3-12, and 3-13 illustrate a caisson-retained island in several aspects, including tow-out of the deballasted caissons.

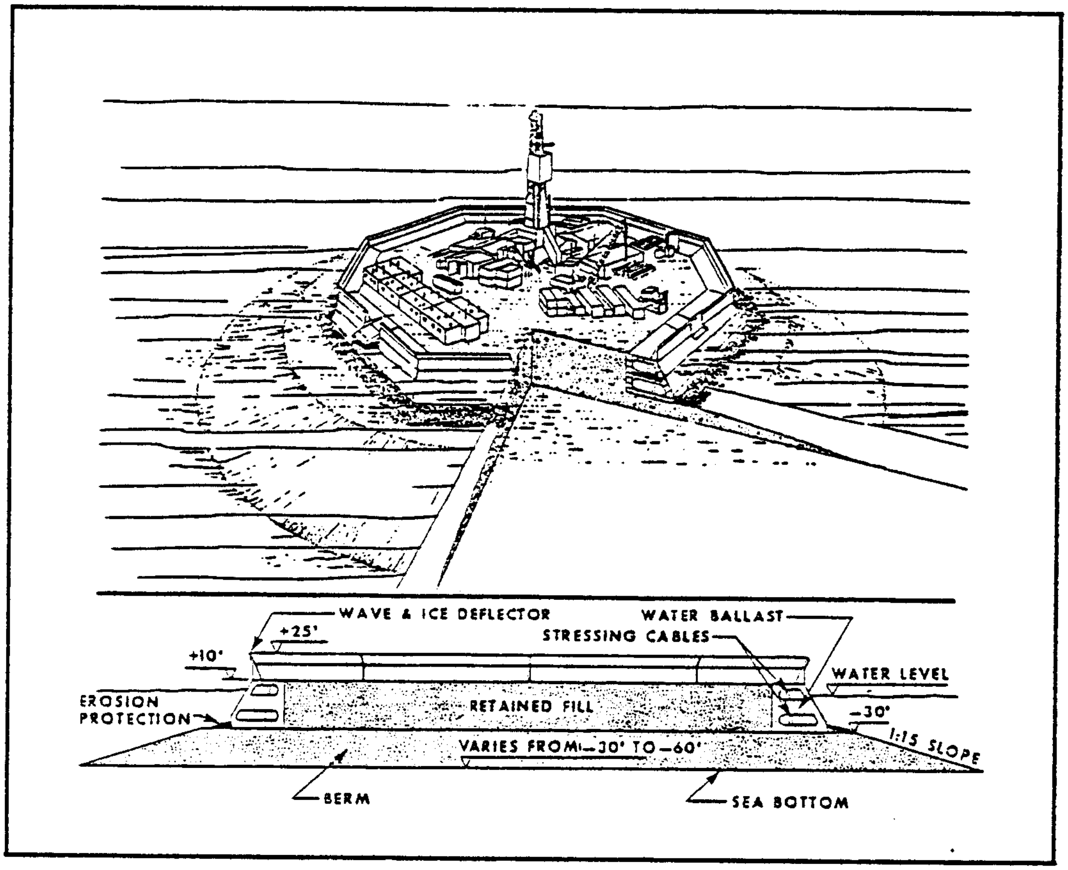
The design illustrated, proposed by Esso Resources Canada (formerly Imperial Oil Ltd.), consists of eight trapezoidally shaped steel caissons, each 43 meters (141 feet) long, 12 meters (40 feet) high with a base of 13 meters (43 feet). The caissons are designed for interlinking by flexible hinge joints and stressing cables. The structural design of the caissons is similar to that of ice-breakers. The caissons are designed for a freeboard of 3 meters (10 feet), which is increased to 7.6 meters (25 feet) by an ice and wave deflector (de Jong and Bruce 1978).

TABLE 3-9

ISLAND FILL REQUIREMENTS

Water Depth Feet	Sacrificial Beach Island Cubic Yards	Retained Fill Island (Sandbags) Cubic Yards	Caisson-Retained Island 30' Set-Down Depth Cubic Yards
20	800,000	250,000	150,000
30	1,700,000	500,000	150,000
40	2,500,000	900,000	300,000
60	5,000,000	2,500,000	900,000

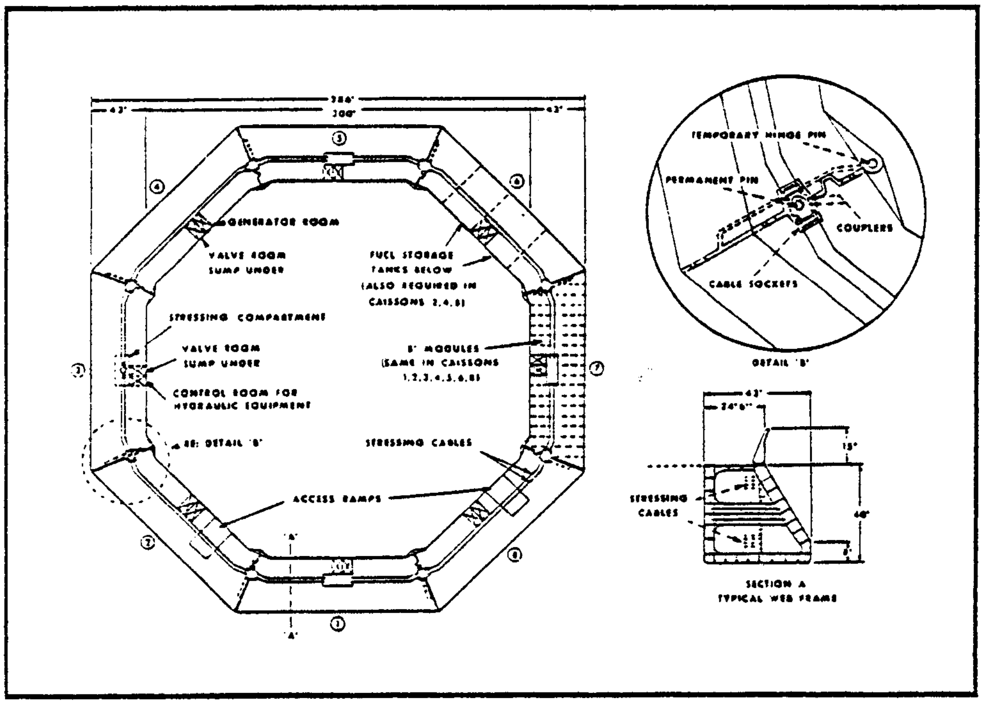
Source: deJong and Bruce 1978.



Source: deJong & Bruce 1978

Figure 3-11

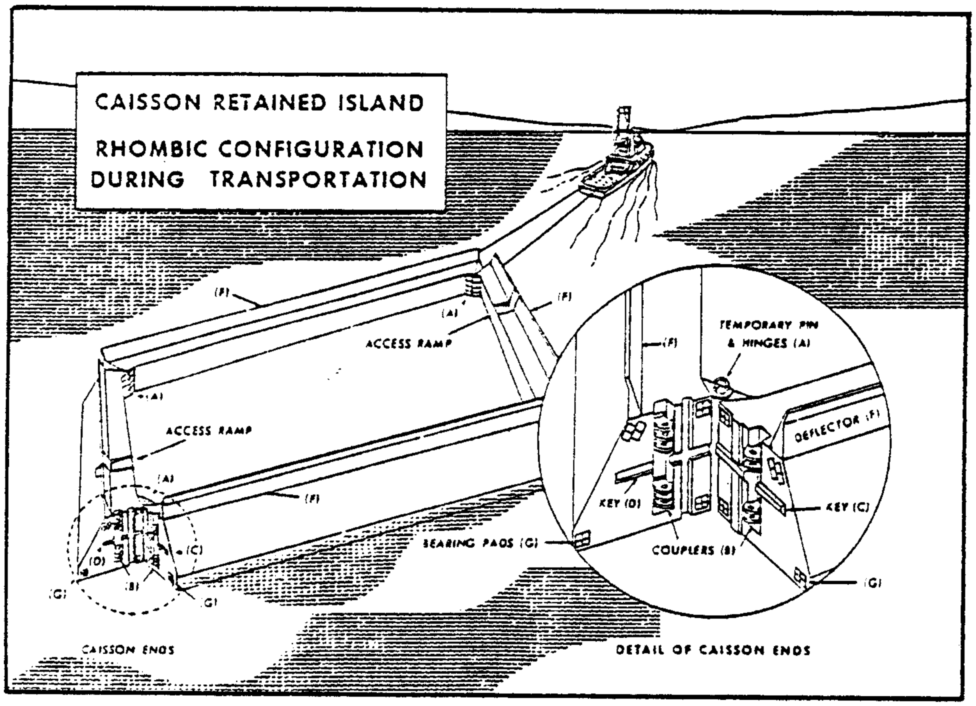
CAISSON-RETAINED ISLAND



Source: de Jong & Bruce 1978

Figure 3-12

CAISSON-RETAINED ISLAND SIMPLIFIED GENERAL ARRANGEMENT



Source: de Jong & Bruce 1978

Figure 3-13

CAISSON-RETAINED ISLAND
RHOMBIC CONFIGURATION DURING TRANSPORTATION

The caisson units will probably be constructed on the west coast and towed via the Bering Strait either singly or in a rhombic configuration in sets of four as illustrated. They could also be barge-mounted for transport to the Chukchi Sea. Once at the island site, the caissons will be set down on a previously prepared underwater berm built up from the sea floor to 9 meters (30 feet) below mean sea level. The berm will be constructed of dredged fill in a fashion similar to the gravel island previously described, although with steeper side slopes.

Once in position, they are secured with pins at corner couplers and stressing cables, then flooded with water to ballast. The center core of the ring is then filled with dredged gravel or sand fill to provide the base for the drilling equipment. The caisson units are equipped with hydraulic stressing jacks, generators, ice-melting heaters, miscellaneous electrical equipment, oil tankers in alternate units, winches, mooring facilities for supply vessels, loading and unloading ramps and a detachable helipad.

One of the intentions of the caisson design is reusability. The caisson ring can be raised and transferred to a new location for exploration drilling each summer after removal of the gravel fill. Once the caissons are deballasted and refloated, they can be disconnected, reassembled for transport and towed to a new site. The system was designed to allow transport of caissons between sites with as little effort and in as short a period as possible. The caissons have a constant set-down depth of 9 meters (30 feet) with the depth variation to the seabed being made up with dredged fill material built into a berm at the new site. However, the only prototype caisson-retained gravel island actually constructed to date, Dome's Tarsiut island, experienced difficulties in construction that may prevent it from being re-used (personal communication, SF/Braun 1982).

Another advantage of the caisson concept is that it eliminates erosion problems encountered in topping out all-fill artificial islands. As soon as the caisson ring is set down it provides sufficient wave protection to prevent erosion losses caused by wave overtopping while the central core is being built up through the wave zone. As a consequence of its reduced fill requirements and ease of assembly, the caisson ring concept reduces the construction time required to build an island and thereby reduces the risk of failing to complete an island during the short open-water season in arctic regions such as the Barrow Arch planning area.

SF/Braun estimates that a construction spread for a caisson-retained gravel island in 15 meters (50 feet) of water would be less than that for a gravel island since less fill has to be moved. The caissons in a caisson-retained island can be constructed of either concrete or steel. While the design discussed here is for a concept using steel caissons, Dome Petroleum Ltd. constructed its Tarsiut caisson-retained artificial island in 22 meters (72 feet) of water in two seasons of construction using four concrete caissons.

As a prototype artificial island, not only is Tarsiut the deepest arctic exploration island constructed to date, it is also the first to actually emplace any type of structure on its fill base. In contrast to Esso's Issungnak gravel island in 19 meters (62 feet) of water which was discussed earlier, Tarsiut's 1.8 million cubic meters (2.3 million cubic yards) of fill is under 40 percent of that used at Issungnak (Cottrell 1981). The two key reasons behind this success were accurate dredge placement techniques that allowed steep side slopes to minimize the fill volume required, and the emplacement of the caissons which avoided the erosion-prone wave zone.

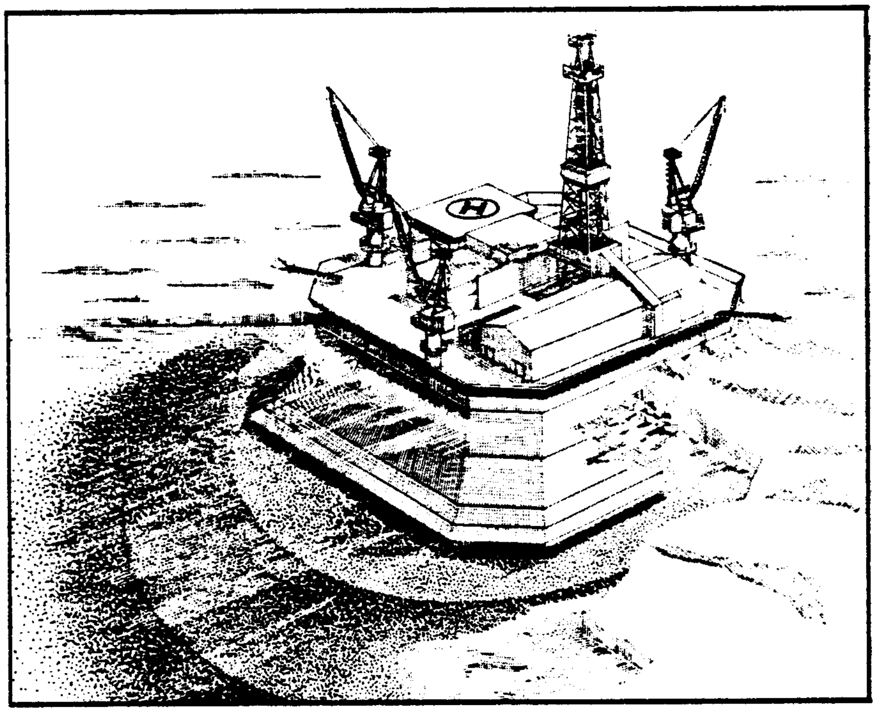
Tarsiut's concrete caissons are each 69 meters (226 feet) long, 15 meters (49 feet) wide and 11.5 meters (38 feet) high, with the gravel berm at 6.5 meters (21 feet) below mean water level, leaving a freeboard of 7.5 meters (25 feet) to the island's surface. The caissons are designed to fail ice by crushing rather than flexural failure so strain gauges and pressure cells have been built into the caissons to measure ice and soil loadings. The caissons were built by forming the bases in dry dock, then floating them out and slipforming to full height in the water. The caissons were constructed of high strength lightweight concrete using air entrainment and the expanded shale aggregate Herculite (Cottrill 1981).

As the water depths over the areas slated for exploration increase, the construction of artificial islands becomes increasingly difficult and costly. Due to the increasing fill requirements and more severe ice conditions, other types of drill platforms for exploration begin to look more attractive. While precise break points between technical concepts have not been delineated, gravel islands become uneconomic somewhere beyond 15 meters (50 feet) and caisson-retained gravel islands fall out beyond 37 meters (120 feet), leaving only one-piece caissons, concrete or steel monocones and ice-breaking drill ships or semi-submersibles as viable drilling concepts for waters out to 60 meters (200 feet) and beyond. According to Chevron, the breakeven depth for all-gravel islands is 18 to 19 meters (60 to 62 feet). Dome believes that its Tarsiut-type caisson-retained gravel islands are feasible for exploration out to 35-meter (115-foot) water depths (Cottrill 1981).

Mobile Caisson Rig

Hybridization of successful artificial island concepts with more traditional concrete and steel structures is evident as technical concepts to explore intermediate (27 meters [90 feet]) to deep (37 meters [120 feet]) water depths. A novel hybrid structure designed for Gulf Canada is a floating annular steel ring to be placed on an island of dredged material and then filled with sand. Weighing about 30,000 tons and constructed using shipmaking bulkhead techniques, the concept is designed to be used for water depths to about 35 meters (115 feet).

Designed to have the capability to operate year-round if necessary, Gulf's mobile caisson rig, pictured in Figure 3-14, is currently under construction in Japan for delivery in March 1984 for a total cost approximating $140 million (Cornitius 1981). The tapered floating steel cylinder will be placed on a sub-surface dredge berm before its center core is filled with sand to provide most of the resistance to the forces from the horizontal movement of ice. The rig is designed to be installed on a simple seafloor foundation, depending upon fill material available. The top of the submarine mound will be brought to 21 meters (69 feet) below sea level so



Source: Cornitius 1981

Figure 3-14

GULF CANADA BEAUFORT SEA MOBILE ARCTIC CAISSON

that the deck of the 29-meter (95-foot) high caisson will stand 8 meters (26 feet) above the water.

After the structure is towed to location and installed on its fill base by water ballasting, the space inside the annulus is filled with clean sand, which is then densified to help resist the ice force applied to the outer hull. The 86-by 86-meter (282 feet) eight-sided top will be the base for the drilling rig and support facilities. The insulated deck will retain heat pumped under the deck to keep the sand core in an unfrozen state. Core fill will be at or below water level with a volume of 115,000 cubic meters (125,000 cubic yards).

The hull configuration is similar to tanker construction with outer-plate, main frames and bulkheads with intermediate stiffeners (Watt 1982). The compartments in the external section of the mobile caisson system will be filled primarily with seawater for ballast. However, the upper sections will be used for storage of fuel and potable water.

After completion of drilling operations, the sand inside the annulus will be removed by suction heads to a level that will permit re-floating and removal of the caisson to a new location. Operations of the arctic mobile caisson rig are supported as necessary by one or more purpose-built Class IV ice breakers and supply vessels (Offshore 1981).

Floating Drilling Units

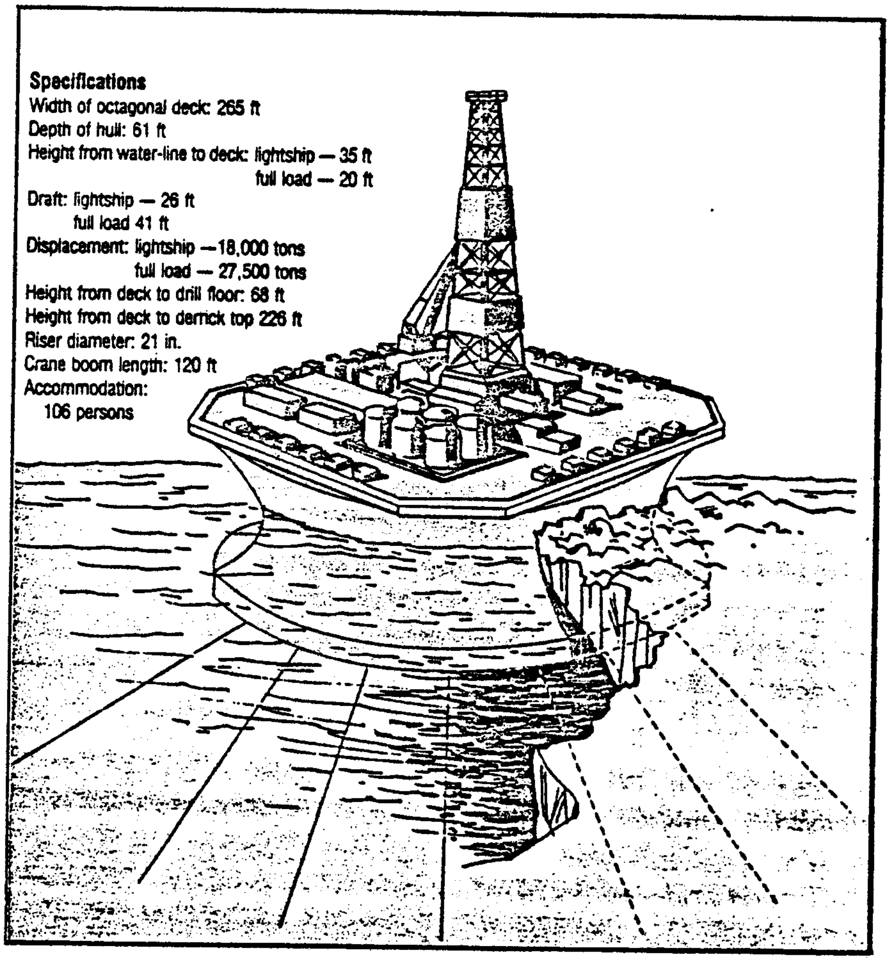
Despite the obvious difficulty inherent in operating floating platforms for arctic exploration drilling, two Canadian operators are proceeding with plans to construct conical floating drilling units for use in deeper arctic waters in the Beaufort Sea. The main purpose of moving to floating drilling platforms, other than ice-strengthened or ice-breaker drillships, is to extend the time period available for exploratory drilling in deeper more ice-infested areas. Dome Petroleum's round drillship and Gulf Canada's conical drilling unit will each be designed to withstand the forces of moving ice thereby extending the floaters' work period for the exploration and delineation phase of development. Such new configurations must also include mooring and riser designs to cope with the generally shallow waters of the Arctic (see Drillships, page 3-68).

Dome Petroleum has replaced its earlier proposals for a swivel drillship, which would have weathervaned into oncoming ice by swivelling around a central turret, with a proposal for a round drillship. The round drillship, intended for year-round drilling in the transition ice with ice-breaker support, is estimated to cost around $125 million. It is proposed as an arctic Class VI moored barge. Its 65-meter (213-foot) diameter hull will contain 10,000 tons of steel and will be shallow and saucer-shaped to offer the smallest possible resistance to ice approaching from any direction. Below the waterline it will draw into a central cone from which the anchor lines radiate outward well below the ice (Cottrill 1981). It will probably be in place by 1984, operating with support from Dome's arctic marine locomotive (AML) ice-breaker Kigoriak and the new AML X10.

Gulf Canada's conical drilling unit, designed for ice Class IV conditions, will be capable of operating from the beginning of June to the end of the following January, ice conditions permitting. The main hull angle slopes at 31° to deflect ice downward and break it. The downbreaking cone shape was selected because total horizontal forces on it are only 20 to 25 percent of what they would be on an upbreaking cone (Offshore 1981).

The unit is non-self-propelled and will be moored on location with 12 anchor cables as pictured in Figure 3-15. Transponders mounted in the seabed and hull will monitor the rig's position over the well location. The control console, which is under the captain's direction, will manage the position and line load using deck-mounted winches.

The hull is of double bottom design, conventional welded-steel ship construction. The ballasting system uses structural compartments for ballast chambers. The circular hull is topped by an eight-sided deck, 80 meters (262 feet) across on which standard drilling equipment is emplaced.



Source: Offshore 1981

Figure 3-15

GULF CANADA BEAUFORT SEA DRILLING BARGE

The conical drill unit will have a heliport capable of handling a Sikorsky S-61 helicopter as well as radar and radio links for communications with shore, marine traffic and aircraft. Instrumentation will record vessel movement and ice loading on the hull and mooring system. Class IV ice-breakers and supply vessels will be available to perform ice management duties, to protect the drilling system as it moves to new locations, to supply bulk materials and equipment to the barge, and to perform other operational functions such as anchor handling.

Ice-Resistant or Ice-Breaker Drillships

Although ice-breaker drillships or ice-reinforced drillships supported by ice-breakers can extend the open-water drilling season somewhat, there is a minimum water depth at which drillships can operate due to limitations on lateral motion or vessel excursion, which are dictated by the riser angle. This depth limitation lies between 15 meters (50 feet) and 20 meters (66 feet). Dome Petroleum has been successful in extending the open-water drilling season with its ice-reinforced Canmar fleet, and this Canadian approach may be applicable in the Chukchi Sea despite the more severe and dynamic ice conditions occurring in the deeper waters in which drillship operations appear desirable.

A second generation of arctic drillships incorporating special hull forms and mooring features to minimize hull forces in moving pack ice, including special features to reduce ice resistance between ice masses and the hull of the ship, once appeared likely. However, the decision of Gulf Canada and Dome Petroleum to order more ice-resistant, conservative designs, indicates the direction in which mobile exploratory drilling concepts are likely to move in years ahead.

Ice-Breaker Semi-Submersible and Jack-up Rigs

Recently, several arctic semi-submersible design concepts have surfaced. While no operators are known to be considering ordering such a system for exploratory drilling in the near future, it is significant that designs are being developed. Such rigs would appear to be particularly applicable in deeper waters of the Chukchi Sea, provided that such concepts were capable of being maintained on station in the dynamic ice conditions found in such waters.

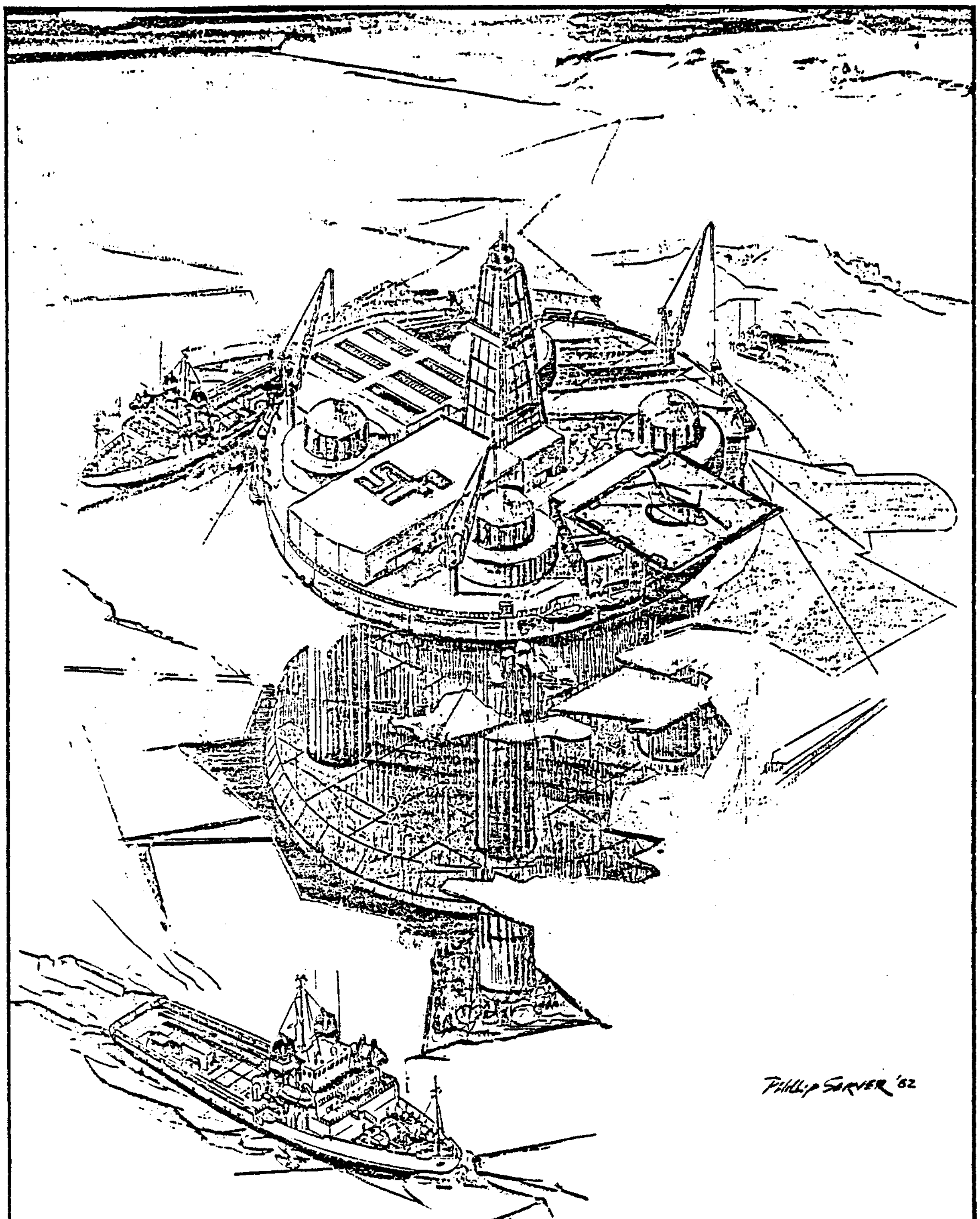
Figure 3-16 illustrates an "arctic drilling barge" concept developed by SF/Braun. The hull diameter is about 90 meters (300 feet) and each leg has a diameter of approximately 12 meters (40 feet). The jack-up will be designed to drill in ice-infested waters in up to 55-meter (180-foot) water depths with a variable deck load of 10,000 short tons.

3.3.2 Production Platforms

3.3.2.1 Background

Production platforms will be positioned over reservoirs to most efficiently develop hydrocarbon resources. The number of platforms needed to tap a reservoir depends on many factors including the area, shape and depth of the reservoir, and how much of it can be drained by a single platform using directionally drilled wells. Drilling and production systems will be concentrated into the fewest number of locations possible.

Selection of production platforms for Barrow Arch oil and gas fields will also depend on several factors. In order to resist the severe ice forces that characterize the Chukchi Sea over the 10- to 20-year life of an average field, bottom-founded platforms will be selected as permanent production systems. Artificial islands will predominate as production concepts, possibly out to water depths as great as 45 meters (150 feet; Harrison 1979). In deeper waters beginning at 37 meters (120 feet), stiff gravity-type structures of steel or concrete are the expected concepts. Such production platforms would include a cone-shaped form at and below the waterline to break advancing ice through flexural failure and to promote ridge clearing without ice pile-up (Harrison 1979).



Source SF/Braun 1982

Figure 3-16
MOBIL ARCTIC DRILL BARGE JACK-UP CONCEPT

Another production-related factor that may be of importance in later development of Chukchi Sea hydrocarbons will be establishing the feasibility of early production systems for arctic conditions. Early production systems have been used in other parts of the world to shorten the lead-time in bringing production on-stream and to allow extended reservoir evaluations prior to commitment of capital for permanent production systems. Such systems assume the existence of a suitable transportation infrastructure.

The production technologies selected in the Barrow Arch planning area will be influenced to a large extent by the exploratory technique used to discover the field when gravel islands or underwater berms are part of the discovery technique. At the present time, exploration technology for offshore arctic areas is significantly more advanced than production technology, reflecting the fact that it is easier to explore for oil than it is to produce it.

No production has at this writing yet occurred from an offshore arctic find anywhere in the world. Although several Canadian operators are currently designing production systems for oil and gas finds that may be produced by 1985 or 1986, there is not the reservoir of experience to draw upon as exists for arctic exploratory drilling technologies. The design concepts presented here are based on current knowledge and expertise. As more research, field data, and operational experience accumulates, design concepts will undoubtedly be modified as necessary by industry operators to improve the final installed technologies. Nevertheless, this report accurately reflects the current state-of-the-art and conceptual technologies for production platforms in the Arctic, and those concepts selected represent in our best judgement systems appropriate to the environmental conditions of the Chukchi Sea.

3.3.2.2 Platforms for the Barrow Arch Planning Area

Selection of production platforms for Barrow Arch reflects a combination of factors including: geographic location, field size, water depth, distance from shore, ice conditions, and transportation systems selected for moving produced oil or gas to market. Any production platform must provide adequate space not only for development drilling but also for processing facilities and crew accommodations.

The trade-offs between artificial island concepts and steel or concrete structures are not well understood for production as opposed to exploration concepts. While artificial islands appear much more favorable at shallow and intermediate water depths, the point at which the economics of steel or concrete structures begin to improve is not well-documented. While early designs for arctic production systems prominently featured monocones or monopods, even for water depths as shallow as 15 meters (50 feet) or less, these structure designs were shelved due to the success of artificial island concepts in the shallower waters. Consequently, monocone designs have only begun to reappear as economic structural configurations in water depths approaching 60 meters (200 feet; Jahns 1980). Economic trade-offs of artificial islands with other structure types depend on the physical location of suitable fill sources and on the operational requirements. Therefore, no definite water depth limit can be given for production platform types. In the Chukchi Sea, duration of the construction season will play a significant role in determining the economic water depth limit for island concepts (National Petroleum Council 1981). Offshore storage can be a major determinant in production structure selection; one arctic production technology (the ALPA, see page 3-10) has developable storage capacity of significant size, and the gravity-type structures also offer storage capability.

In addition, the comparative advantages of various production platforms over others in terms of offshore installation times are not well known. While the length of the open-water season is a critical construction and installation constraint, no experience in shifting from an exploration to production concept in arctic areas has been accumulated although several Canadian fields are on the verge of such choices. Concrete or steel structures have the advantage of being fabricated in an environment free of ice constraints, with tow-out and installation requiring good open-water conditions. No experience in expanding an artificial island from an exploration base into a production mode has yet been obtained. It is unclear in advance what advantage if any, hybrid production concepts emplaced on exploratory artificial islands may have. Such trade-offs will be site-, design- and operator-specific. Clearly, a successful exploration gravel island at a newly discovered producible reservior represents a valuable asset for oil recovery from at least a portion of the field.

As expected, ice loading forces on Barrow Arch production platforms are the controlling design factor. Structures must be able to survive in the shear zone between land-fast and moving pack ice and impacts of the multi-year pack ice itself. Natural ice floes or islands also present a potential hazard in the Chukchi Sea. Feasibility of different structural concepts is principally predicated on their ability to resist ice loads effectively.

The principal design criteria for a Barrow Arch structure are:

- Ice loads
  - adfreeze*
  - multi-year ice
  - first year sheet ice
  - rubble piles
  - impact forces due to ice floes during open and partial open water
- Water depth
- Wave loads
- Currents
- Temperature
  - minimum air
  - maximum air
  - minimum water

---

* Adfreeze is the adhesion or bonding of failed ice rubble to an offshore structure which is usually counteracted by heating or treatment with anti-bonding surfactants such as Zebron, which reduce the friction coefficient.

- o Competency of seafloor soils
- o Dredge fill availability (if dredge fill is required)
- o Open-water season requirement
- o Service life
- o Installation and fabrication capabilities
- o Number of conductors and spacing
- o Seismic loading
- o Topside facilities
- o Transportation means (pipeline or tanker).

A constraint on the number of well slots exists for one type of Barrow Arch production platform but not the others. Due to the limited diameter of a steel or concrete monocone's vertical throat, space for a limited number of wells can be provided within the platform. Another constraint is the maximum number of wells that can be directionally drilled from one platform into the reservoir. We have assumed 60 wells, of which 15 to 20 wells are reserved for water and gas reinjection. Fewer than 15 service wells may suffice for gas reinjection only, and more than 20 may be needed for a complete waterflood program. Based on 60 wells, a monocone of 17 to 18-meter (55 to 60-foot) diameter would be needed. More wells would require a greater diameter at the waterline, increasing environmental forces that would increase the base width and thus platform design and fabrication costs.

Some alternatives for increasing the number of wells are:

- o If more wells can be drilled into the reservoir from a single platform, the cone diameter might be increased. However, allowance must be made in this case for increased wave forces and ice loading on the structure.

- o Subsea satellite wells can be drilled with flowlines back to the drilling/production platform. Maintenance for these wells might include TFL (through flowline) methods.

- o Independent drilling (only) platforms can be installed and the unprocessed crude flowed back to the production platform for processing.

The water depths considered for this study are relatively shallow and range from 15 to 60 meters (50 to 200 feet). This water depth range is very similar to the depth ranges of proposed Alaska Beaufort Sea platforms as well as some of the platforms presently being designed for Canada's Beaufort Sea finds. The following types of production platforms appear feasible for the Barrow Arch planning area at the following water depths:

<u>15 meters (50 feet)</u>

- o Gravel-fill production island
- o Caisson-retained gravel production island

<u>27 meters (90 feet)</u>

- o Caisson-retained gravel production island
- o Steel or concrete monocone/gravity island
- o Arctic production and loading atoll (APLA)

<u>37 meters (120 feet)</u>

- o Caisson-retained gravel production island
- o Mobile caisson production rig
- o Concrete gravity island
- o Steel or concrete monocone/gravity island
- o Arctic production and loading atoll (APLA)

<u>60 meters (200 feet)</u>

- o Steel or concrete monocone/gravity island
- o Arctic production and loading atoll (APLA)

3.3.2.3 Well Slot Limitations

One of the technical constraints of the monocone platform design with its conductors located within the vertical throat or shaft is a limitation on the number of well slots that can be housed on a production platform. In a conventional (e.g., Gulf of Mexico) platform, there are few constraints as to the number of well slots that can be incorporated into the design since the conductors are open and pass through conductor guides at horizontal bays in the jacket. However, in an area affected by sea ice, such as the Barrow Arch, open-well conductors cannot be considered. In the Cook Inlet designs, the larger the legs can be made, the greater the number of conductors that can be accommodated. However, as the diameter increases, so do the ice forces; therefore, additional internal stiffening is required, which reduces the number of conductors inside the legs. The same principle applies to monocone gravity-base structures.

For this analysis, the diameter of a monocone shaft is assumed to be on the order of 16 to 18 meters (55 to 65 feet). In this range, the total number of well slots would be limited to on the order of 48 to 60, depending on the size of the conductors and design criteria. Based on these ice-resistant design considerations, the maximum number of well conductors that we have assumed in a closed conductor platform design is 60. Anything over 60 could become a considerable design problem in order to resist very high ice loads.

3.3.2.4 Platform Construction, Transportation, and Installation Techniques

Techniques for installing these platforms in the Barrow Arch are a sensitive part of the project development.

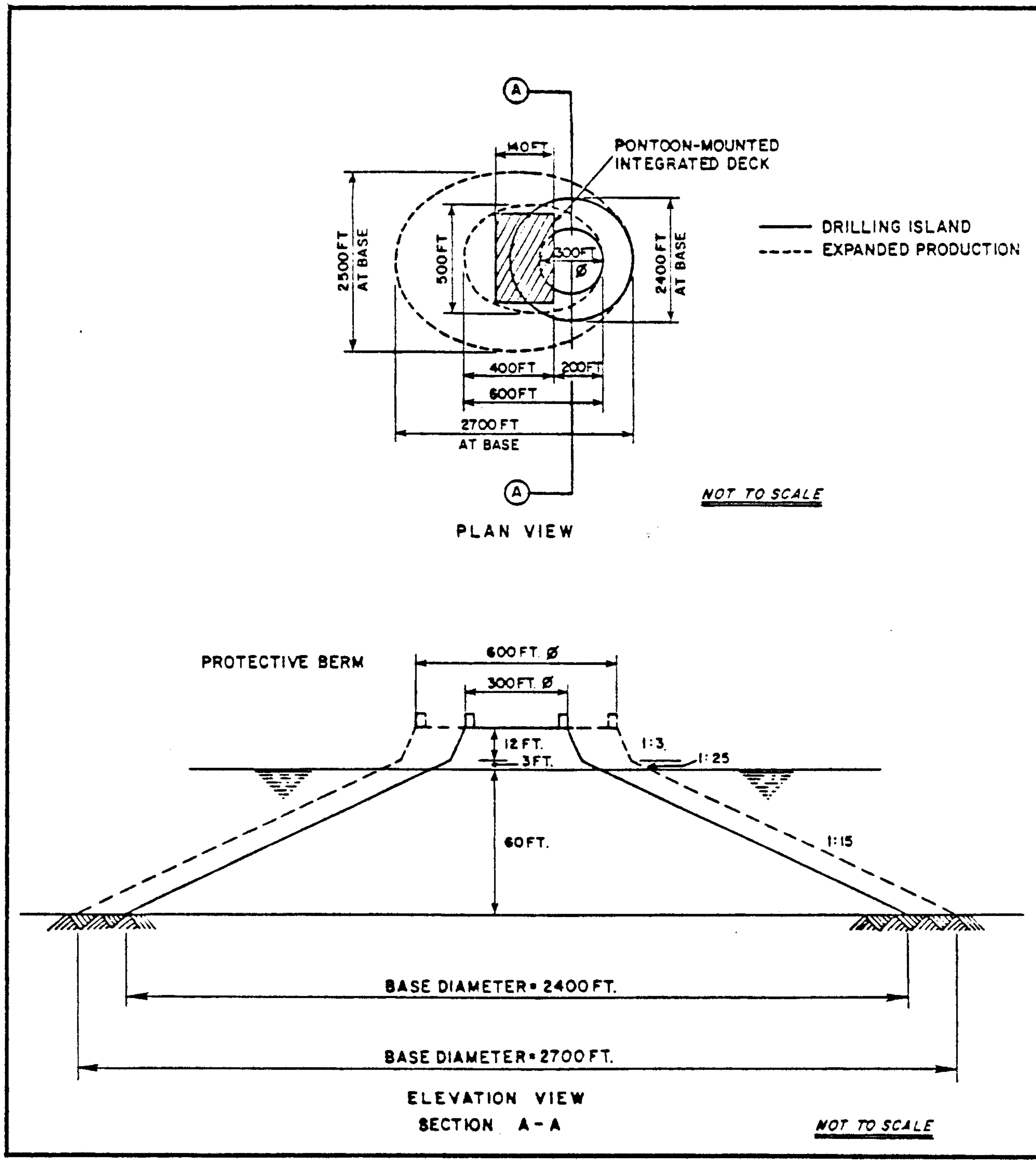
Artificial Island Concepts

Because of their larger size and permanent slope protection, production islands will be substantially more expensive than temporary islands for exploration drilling. The cost is a function of water depth, island size, soil conditions, underwater slope, freeboard, construction season, fill availability, distance from shore and the type of armor units used in slope protection. Finding the most cost-effective slope angle and construction method with locally available materials will be a major objective of site-specific design efforts (National Petroleum Council 1981).

For permanent production islands, a passive design against lateral ice loads will be required (Jahns 1980). Active defense measures, other than monitoring of ice conditions, will not be economically or operationally attractive for long-term, year-round production operations. Thus the design of production islands will have to accommodate more extreme ice events than is the case for temporary islands. This is accomplished by increasing the size and freeboard of the island.

- <u>Gravel-fill Production Island</u> - A construction procedure similar to that described for an exploration island will be required. Assuming that an exploration island is expanded into a production island, dredges are employed to expand the island's base and fill profile once open-water season arrives. The island's diameter above water might be expanded from 90 to 150 meters (300 to 500 feet). It is likely that drilling, production and processing equipment will be modularized, barge-mounted and floated in once the structure is complete. Expansion of an exploration island into a production island can be accomplished in one average open-water season, although if a larger production island is constructed from scratch, two seasons will be required. Figure 3-17 illustrates an expanded arctic production gravel island.

- <u>Caisson-retained Gravel Production Island</u> - Although only exploration designed caisson islands have been built to date, it is assumed that larger caissons and a larger fill berm are all that are required to expand this exploration concept for development. Construction procedure will be the same as for the exploration concept described earlier and production and drilling



Source: National Petroleum Council 1981

Figure 3-17

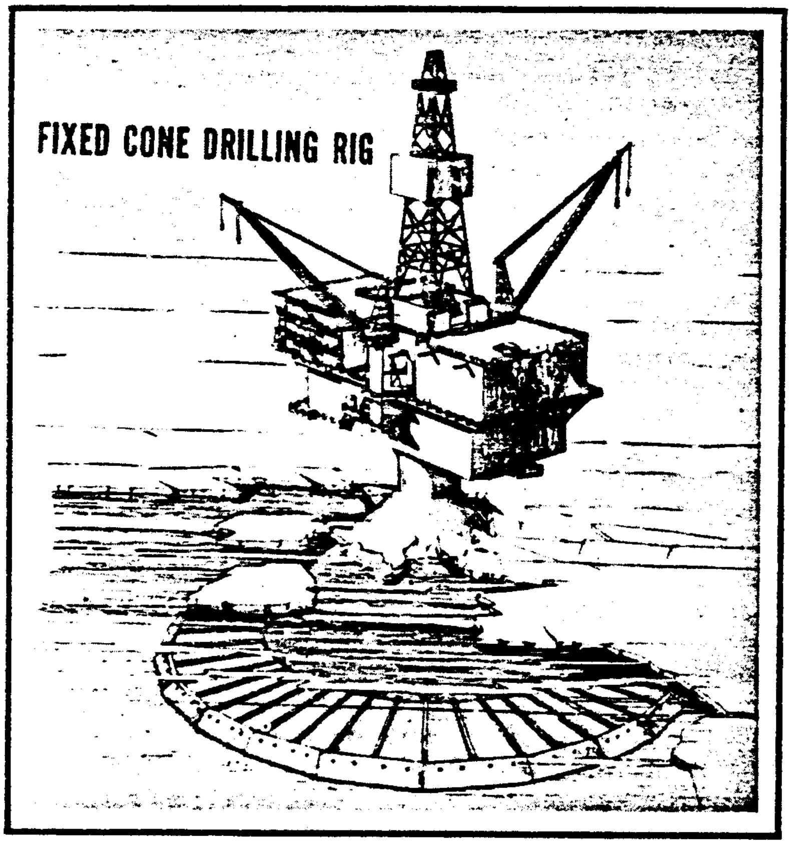
ARCTIC EXPLORATION DRILLING & EXPANDED PRODUCTION ISLAND

equipment is likely to be barge-mounted and modularized for easy installation.

- Mobile Caisson Production Rig - A larger caisson will have to be designed, constructed and floated out in order to develop this production configuration. Once the exploratory rig is de-ballasted and floated away, dredges can expand the fill berm to accept the production structure. It is not sure what deckload, if any, this concept could handle during tow-out.

- Steel or Concrete Monocone/Gravity Island - Monocone and other gravity island concepts have been studied by several operators, including Esso Resources Canada, Dome Petroleum and Exxon. The main principle of the concept is to expose a conical suface to invading ice so that it is broken up by flexure rather than by crushing, thus reducing ice forces. Both concrete and steel structures have been proposed. Steel offers the advantage of high strength and low weight, but in deeper waters a concrete structure's draft limitations are eased. A massive concrete gravity island offers potential for storage capacity, serving as an offshore loading structure.

Figure 3-18 illustrates a concept developed by Esso Resources Canada. The structure consists of a large diameter circular hull, a cone section with a 45° cone angle and a 12-meter (40-foot) diameter at the top, and a multistory deck section. The hull is designed for impact by deep-heeled ice features and serves two main functions. The first is to provide resistance against sliding and overturning when the structure rests on the bottom. The second is to provide buoyancy when deballasted so that the structure can be towed while floating on its hull in a stable configuration and with minimum draft. The particular structure illustrated, an exploratory concept, was designed for water depths from 20 to 40 meters (70 to 135 feet; Jahns 1980). Other designs developed by Esso Resources Canada are for water depths to 60 meters (200 feet).



Source: Jahns 1980

Figure 3-18

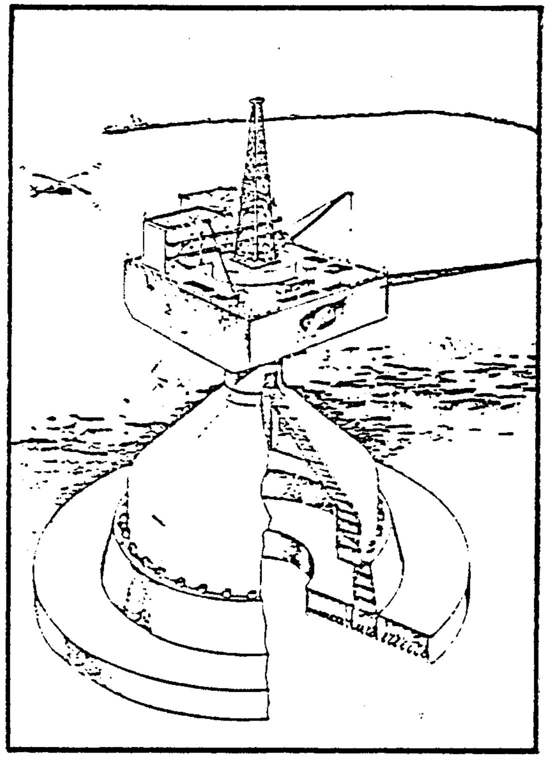
ESSO RESOURCES ARCTIC MONOCONE

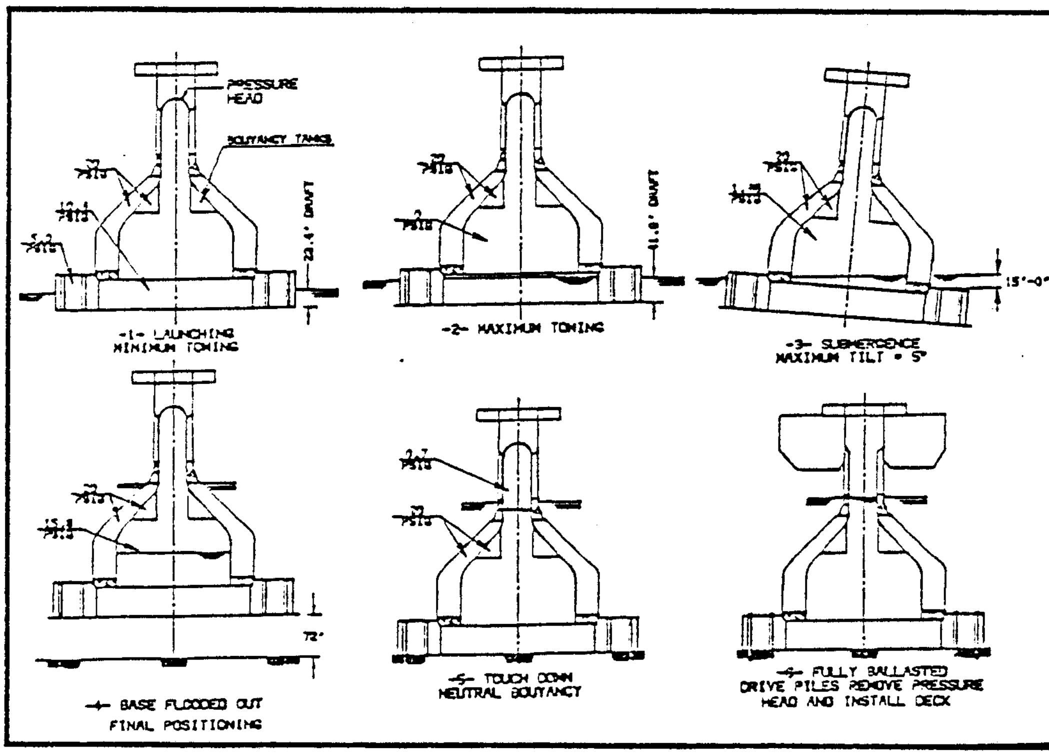
Cone and monocone designs developed to date are designed to resist large multi-year ice pressure ridges up to 14 meters (45 feet) thick. If more severe ice loadings are anticipated, cone angles of less than 45° may be considered. Extensive model studies have been conducted to determine the ridge loads that are developed on cones with different slope angles. Other model tests have been conducted to determine wave loads and to observe the floating stability of cone structures during tow and installation. Lease sales held prior to the Barrow Arch sale will provide strong incentives for industry to further develop and field test such advanced development concepts for the Arctic.

Another monocone design developed for Dome Petroleum Ltd. is illustrated in Figure 3-19, which also shows its tow-out and installation. The structure is designed to cause failure and permit clearing of sheet and ridge formations and has a capability to disconnect at the cone-base interface in case of impending ice island collision. For design load resistance, the rotational inclined plane formed by the cone serves to fail ice ridges in flexure, while the slender throat minimizes ice sheet crushing failure and clearing forces. The impact of a small ice island of average draft and properties can also be absorbed (Bercha and Stenning 1979).

Although it is unlikely that a structure installed on the central Chukchi shelf would be endangered by an ice floe or island, the structure illustrated has the design capability to be disconnected from its base and floated out of the path of oncoming ice islands. The bottle mid-structure can be disconnected from the base by unlocking anchor pins, jacking down the deck and floating the assembly out of the ice island's way.

Different opinions exist regarding the selection of steel or concrete for a monocone design. SF/Braun selected concrete as the preferred construction material for monocone concepts to be installed in the Chukchi Sea. A concrete structure's heavier weight requires less ballast than a comparable steel concept. Concrete also possesses local strength superiority to resist buckling from local ice loads in comparison to steel. A concrete structure also has a superior insulation coefficient and a larger potential for storage capacity.





Source: Bercha & Stenning 1979

Figure 3-19

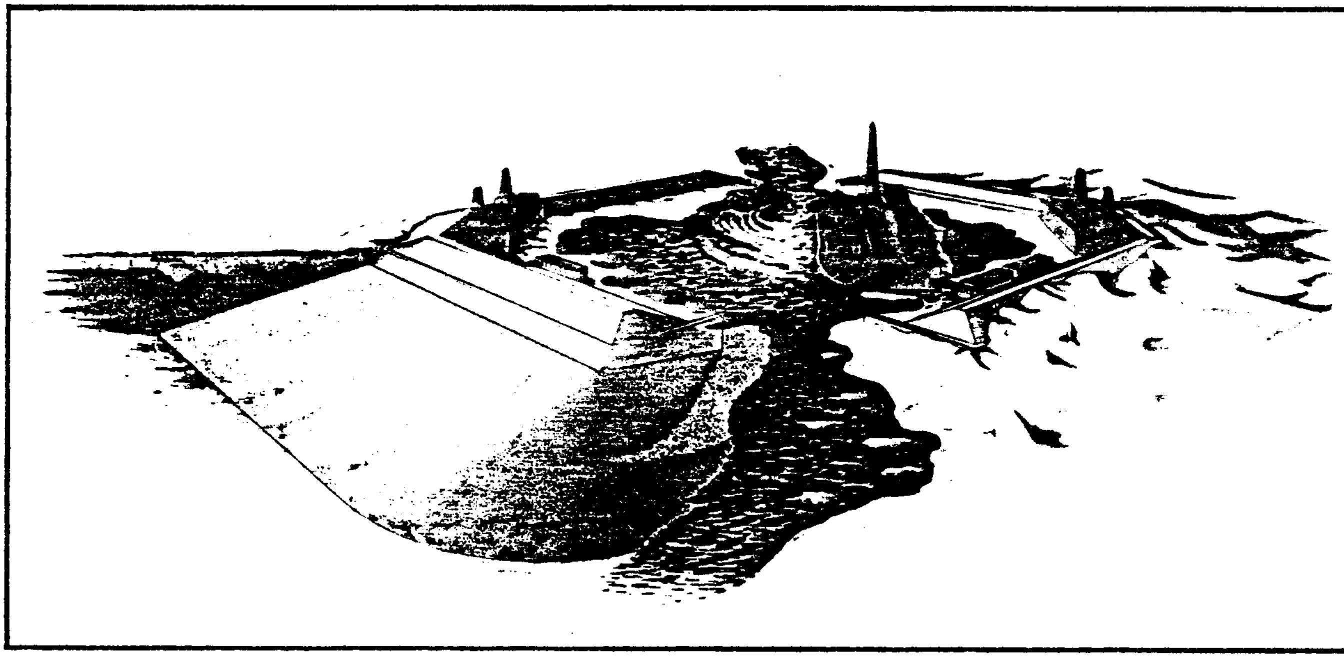
DOME PETROLEUM ARCTIC MONOCONE CONFIGURATION, TOWING & INSTALLATION

However, steel appears to be preferred by some operators over concrete as a construction material for monocones because of its superior abrasion resistance to sea ice. It can also be more easily treated with non-stick coatings such as Zebron to resist adfreeze or heated to achieve the same effect. Steels for arctic application must satisfy the usual criteria of strength, ductility, toughness and weldability. A number of steels are available for low temperature applications. This is important since the loads in an arctic structure caused by temperature differences can be severe.

It is assumed that steel or concrete monocone concepts will be constructed on the west coast and towed through Unimak Pass, the Bering Sea, through the Bering Strait into the Chukchi Sea. As soon as ice conditions permit, the structures will be towed to its final installation site, ballasted down, and either piled or grouted to the sea floor. Unless ice gouges on the sea bottom are present, it is expected that a minimum of site preparation will be required during installation. The floated-out monocone can also carry a substantial load of deck equipment in-place during tow-out with the remainder being barge-mounted and installed on deck by derricks.

Arctic/Artificial Production and Loading Atoll (APLA)

A novel production concept incorporating field production and offshore loading has been developed by Dome Petroleum Ltd. for use in its Mackenzie Delta reservoirs. Dome proposes to construct and operate offshore island terminals called arctic production and loading atolls (APLA) or artificial production and loading atolls (APLA) or arctic production and loading basins (APLB). Constructed from dredge fill in a manner similar to an artificial island, an APLA, pictured in Figure 3-20, would consist of two massive berms capped with concrete caissons. The atoll-like island will provide protection from ice in its "lagoon" basin for drilling and/or production barges and tanker loading facilities. An APLA-mounted terminal would provide docking and transfer facilities for ice-breaking tankers. The island's onshore area serves to support drilling and production facilities with



Source: Ocean Industry 1981

Figure 3-20

DOME PETROLEUM ARTIFICIAL PRODUCTION & LOADING ATOLL (APLA)*

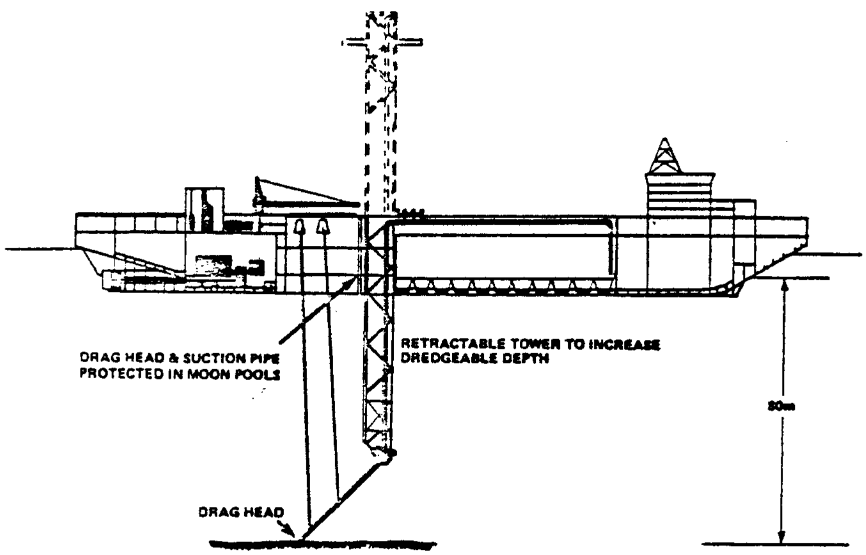
*ALSO "ARCTIC PRODUCTION & LOADING ATOLL" storage capabilities. Storage or production facilities could be increased through the use of slave tankers moored within the APLA.

Dome is examining the use of APLA's as a deepwater development concept in waters of 60-meter (200-foot) depth. Depending upon reservoir shape and size, an APLA may service a field entirely from directionally drilled wells, or be supplied by pipeline from smaller artificial islands equipped with drilling and production facilities to accommodate development of the extremities of the larger fields.

An integral part of an APLA's feasibility is its construction by so-called "super dredges" which will have far greater capacity than the largest currently available conventional dredges. Dome estimates that an APLA in 60 meters (200 feet) of water will require between 80 and 120 million cubic meters (100 and 160 million cubic yards) of dredged materials. Dome plans on using three or four "super dredges" to construct each deepwater APLA, with each "super dredge" available to do the work of three large conventional dredges.

Dome has calculated that it can reduce the cost of an APLA's or artificial island's construction by a factor of 24 through a combination of developments it is pursuing (Cottrill 1981). New "super dredges" should reduce unit costs by a factor of three through their greater capacity and extended season of operation, while steep slopes reduce the volume of fill required to about one-eighth of that previously needed. Dome estimates that an APLA in 60 meters (200 feet) of water would cost between $3 and $4 billion, not including the costs of the ice-breaking tankers.

Dome has placed an order for delivery of its first "super dredger" by May of 1983. It is estimated to cost $100 million. The dredge is designed to have 2.5 times the capacity of the largest existing hopper suction dredger, the Geopotes 10. Dome's planned "super dredge," pictured in Figure 3-21 has the following special features:



SPECIAL FEATURES

1. RETRACTABLE TOWER TO EXTEND DREDGEABLE DEPTH TO 80m.

2. DRAG HEAD & SUCTION PIPE PROTECTED FROM ICE BY MOON POOL ENCLOSURES.

4. ICE BREAKING CLASS 6 HULL WITH BOW REAMERS.

Source: Ocean Industry 1982

Figure 3-21

DOME PETROLEUM
ARCTIC SUPER DREDGE

- Year-round operation in transition ice without ice-breaker support, through an arctic Class VI hull, bow reamers and extreme ice-breaking devices.

- Hopper capacity of at least 25,000 cubic meters (33,000 cubic yards).

- Dredgable depth that can be extended to 80 meters (260 feet) using a retractable tower amidships, allowing high accuracy for subsidiary tasks like trenching and removal of clay overburden.

- Power plant of 60,000 horsepower allowing 25,000 cubic meters (33,000 cubic yards) to be loaded in two hours and 16 knots of sailing speed.

- Drag head and suction pipe in a moon pool, protected from ice (Cottrill 1981).

"Deepwater" Arctic Production Technology

While "deepwater" for the purposes of this study was defined as those water depths beyond 30 meters (100 feet), which reflects industry's current experience to date with exploration concepts in the Arctic, several production concepts for water depths beyond the 37-meter (120-foot) water depth selected as the representative deep water depth in the Barrow Arch planning area were also examined.

According to SF/Braun, two technical approaches seem feasible for development of oil and gas finds in areas of the Chukchi Sea with water depths of 60 meters (200 feet). The most economic approach would be emplacement of a monocone structure designed for shallower water depths, say 37 meters (120 feet), onto a base built up by dredged gravel fill to a height of 24 meters (80 feet) above the seafloor.

A second approach would be emplacement of a monocone specifically designed for 60-meter (200-foot) water depths. However, the costs of such a structure could be significantly greater than the first option, depending on gravel availability.

Dome Petroleum proposes to construct its APLA's in water depths up to 60 meters (200 feet). For such a concept to be viable in the Chukchi Sea, U.S. operators would have to commission "super dredges" similar to those planned by Dome.

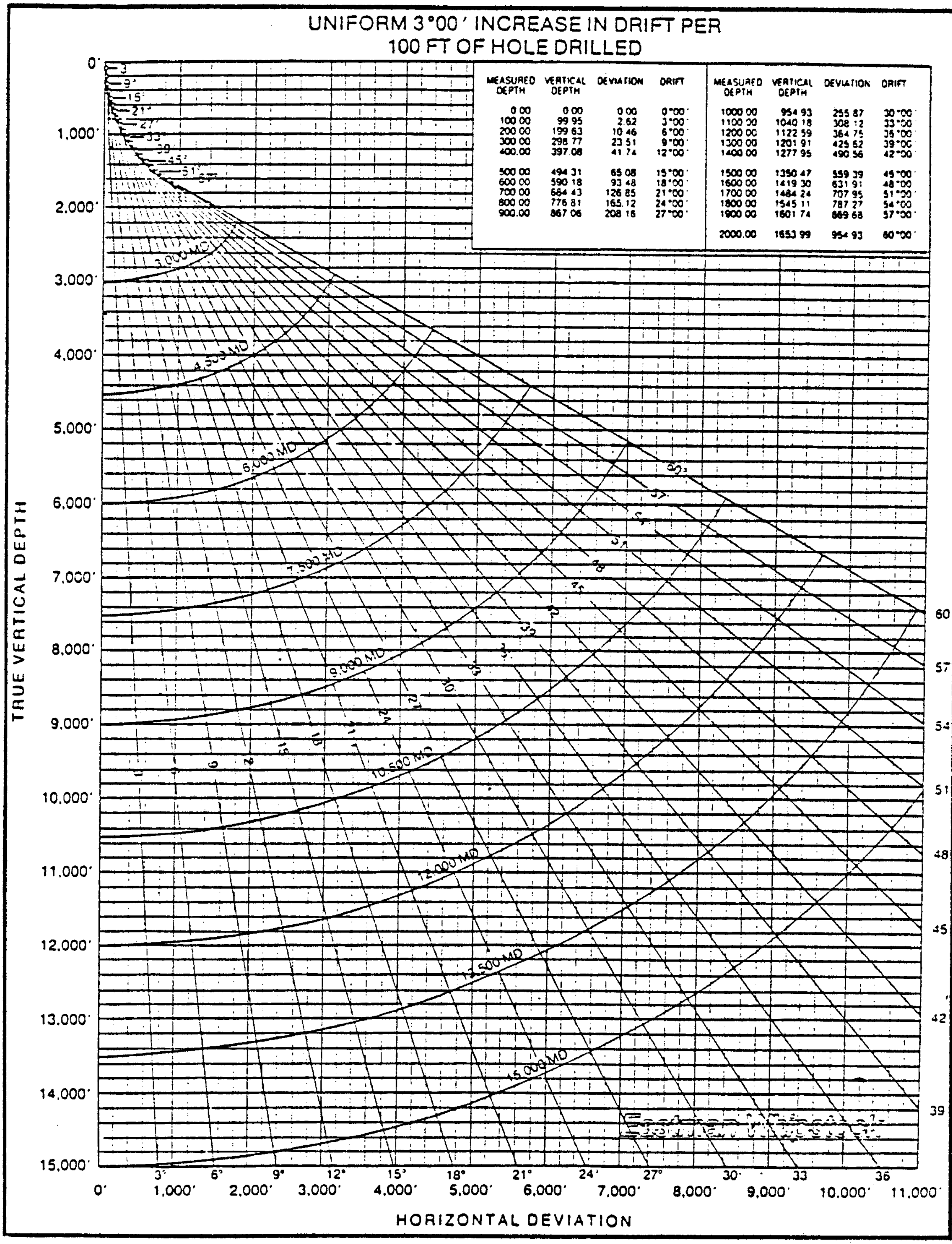
3.3.3 Wells

Most production wells will be drilled directionally from the production platforms. The production concepts suggested for the Barrow Arch planning area have constraints on the maximum number of wells. Artificial island production concepts might each accommodate a total of about 100 wells, which can be slant drilled if required, but the total number of wells possible is a direct function of the amount of area constructed. Monocone production concepts can only accommodate a maximum of around 60 wells per structure, due to the limitation on throat diameter, and slant drilling will not be possible (see discussion in Section 3.3.2.3).

There are also technical limitations (as well as cost premiums) on directional drilling for angles of over 50°. A graph showing a typical rate of increase in drift for the generally adopted maximum slant angle of 60° is shown on Figure 3-22. Depending on seabottom soil conditions, a typical kick-off point(1) would be about 150 to 300 meters (500 to 1,000 feet). With conductors located within the legs of the structure, directional drilling is a part of the constraints to total number of wells and the subsurface area the platform can drain.

Development well drilling will begin as soon as feasible after platform installation. If regulations permit, the operator may elect to begin

(1) Kick-off point = the depth where the traverse departs from the vertical in the direction of the target.



MEASURED DEPTH	VERTICAL DEPTH	DEVIATION	DRIFT
0.00	0.00	0.00	0°00'
100.00	99.95	2.62	3°00'
200.00	199.63	10.46	6°00'
300.00	298.77	23.51	9°00'
400.00	397.08	41.74	12°00'
500.00	494.31	65.08	15°00'
600.00	590.18	93.48	18°00'
700.00	684.43	126.85	21°00'
800.00	776.81	165.12	24°00'
900.00	867.06	208.16	27°00'
1000.00	954.93	255.87	30°00'
1100.00	1040.18	308.12	33°00'
1200.00	1122.59	364.75	35°00'
1300.00	1201.91	425.62	39°00'
1400.00	1277.95	490.56	42°00'
1500.00	1350.47	559.39	45°00'
1600.00	1419.30	631.91	48°00'
1700.00	1484.24	707.95	51°00'
1800.00	1545.11	787.27	54°00'
1900.00	1601.74	869.68	57°00'
2000.00	1653.99	954.93	60°00'

Source: Eastman Whipstock, Inc.

Figure 3-22

DIRECTIONAL DRILLING CHART

drilling while offshore construction is still underway, accepting some interference between the two activities. The operator has to weigh the economic advantages of early production versus delays and inefficiencies in platform commissioning. Development drilling could commence about 10 months after the selected development concept is installed on site[1]. Development wells may be drilled in a "batch" where a group of wells are drilled first to the surface casing depths, then drilled to the next smaller casing depth, etc. (Kennedy 1976). The batch approach not only improves drilling efficiency but also improves material-supply scheduling. However, this does not provide timely geological information for planning the later wells.

On artificial island concepts and monocones, two drill rigs may be used for development well drilling, thus accelerating the production schedule. One rig may be removed after completion of all the development wells, leaving the other rig for drilling injection wells and performing well maintenance.

Permafrost could be encountered in parts of the Barrow Arch planning area. Therefore, wells will be completed with casing programs, cementing techniques and tubing strings similar to those used on the North Slope (National Petroleum Council 1981). Figure 3-23 illustrates a typical permafrost casing program.

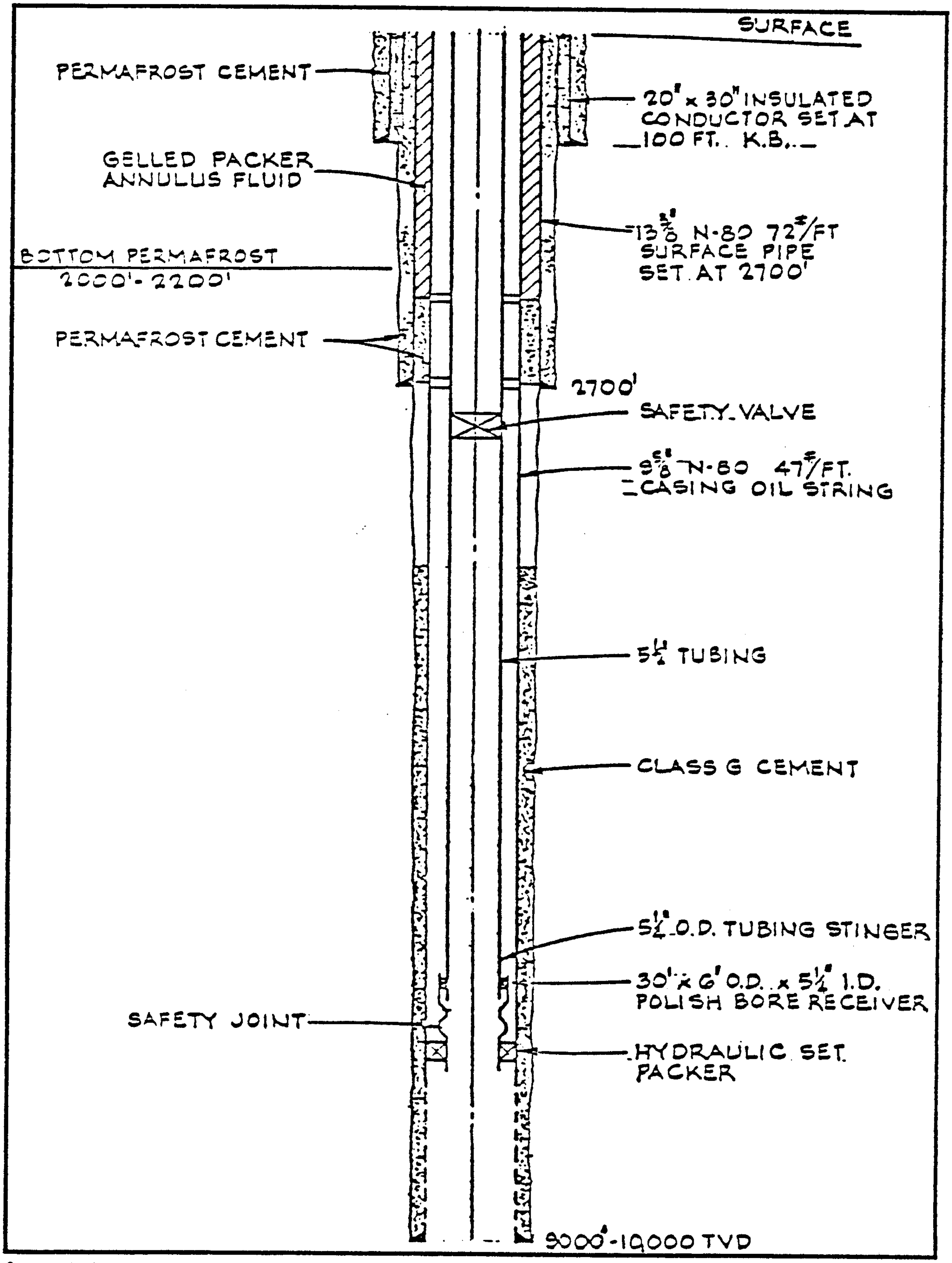
3.3.4 Pipelines

Marine pipelines will be required to transport oil and gas from the Barrow Arch fields to shore terminals for further processing and tanker transport to market or to shore for pipelining to TAPS and on to market. Several pipelay techniques have been devised for use in arctic conditions.

The most important engineering design considerations for pipelines in the Barrow Arch planning area are:

---

(1) See Sections 6.2.3 and 7.2 for detailed discussions of the timing assumptions made in our analysis.



Source: National Petroleum Council 1981

Figure 3-23

TYPICAL PERMAFROST CASING PROGRAM

- o Depth of ice scour
- o Subsea permafrost
- o Ice override events in the coastal zone
- o Low pressure water jets from strudel scour
- o Geotechnical problems related to seabed soils
- o Coastal erosion
- o Limited open-water construction season
- o Water, crude, and gas temperatures.

In pipelaying technology there are five areas requiring careful analyses and solution:

- o Prediction of pipe stress during installation
- o Control and knowledge of exact pipe location during lay operations
- o Joining with an offshore riser
- o Protection of applied coatings
- o Design and implementation of the shoreline crossing.

Although arctic offshore pipelay technololgy is in its infancy, the strong technical base acquired from offshore operations in other areas gives a reasonable assurance that pipelaying can be successfully accomplished in the Chukchi Sea.

Only one pipeline has actually been laid in arctic conditions, a proof-of-concept demonstration held in the Canadian Arctic to lay a natural gas pipeline from an offshore wellhead to Melville Island for Panarctic Ltd. This demonstration employed what is called the Ice Hole Bottom Pull Method. A trench was cut through the ice and on-ice winches were used, first to pull an underwater plow to trench the seabed and then to deploy the pipeline. A remotely controlled connection module was used to connect the pipeline to the wellhead. However, this winter construction technique cannot be used in the Chukchi Sea since it requires a smooth landfast ice surface on which to operate.

Therefore, open-water pipelay techniques seem most feasible for laying marine trunk and feeder pipelines to service Barrow Arch oil and gas fields. Four different methods of pipe-laying developed for non-arctic operations may be adapted for use during the short open-water season in arctic areas. These are:

- o Bottom-pull or bottom-tow method
- o Flotation method
- o Reeled pipe method
- o Lay barge method.

Of these, the bottom-pull method has been touted as most feasible for arctic operations (Timmermans 1982). In this method, lengths of pipe section are welded onshore and then pulled along the sea bottom. A winch firmly anchored on a barge is used as the pulling force. The method requires construction of a mile-long gravel pad onshore that is used as a staging area to pre-weld pipe sections.

However, the National Petroleum Council (1981) believes that conventional pipelay systems will not be practical in the Chukchi Sea for a number of reasons. They prefer the bottom-tow method and believe that the sizable onshore pipe assembly site can be used later as part of the oil storage facilities. They also believe that ice conditions will make it difficult to time the arrival and exit of the pipeline spread to get the job done in one season. If the spread happens to be iced in and remains inactive for 10 months, costs could run as high as $150 million per year.

The length of the pipeline pulled is limited to relatively short offshore distances because of rapid increase of pulling force with distance (Energy Interface Associates 1980). Because of this, and the brief working season for the longer Barrow Arch pipelines, SF/Braun assumes conventional ship-type lay vessels for this cost analysis (Appendix B, Table B-5).

Assuming a 70-day open-water season in the Chukchi Sea, SF/Braun believes that a conventional lay vessel could lay close to 80 kilometers (50 miles) of pipe per season. This assumes downtime of 10 percent due to weather and an average lay rate of 1.2 kilometers (3/4 mile) per day assuming a pipe diameter of 22 to 30 inches.

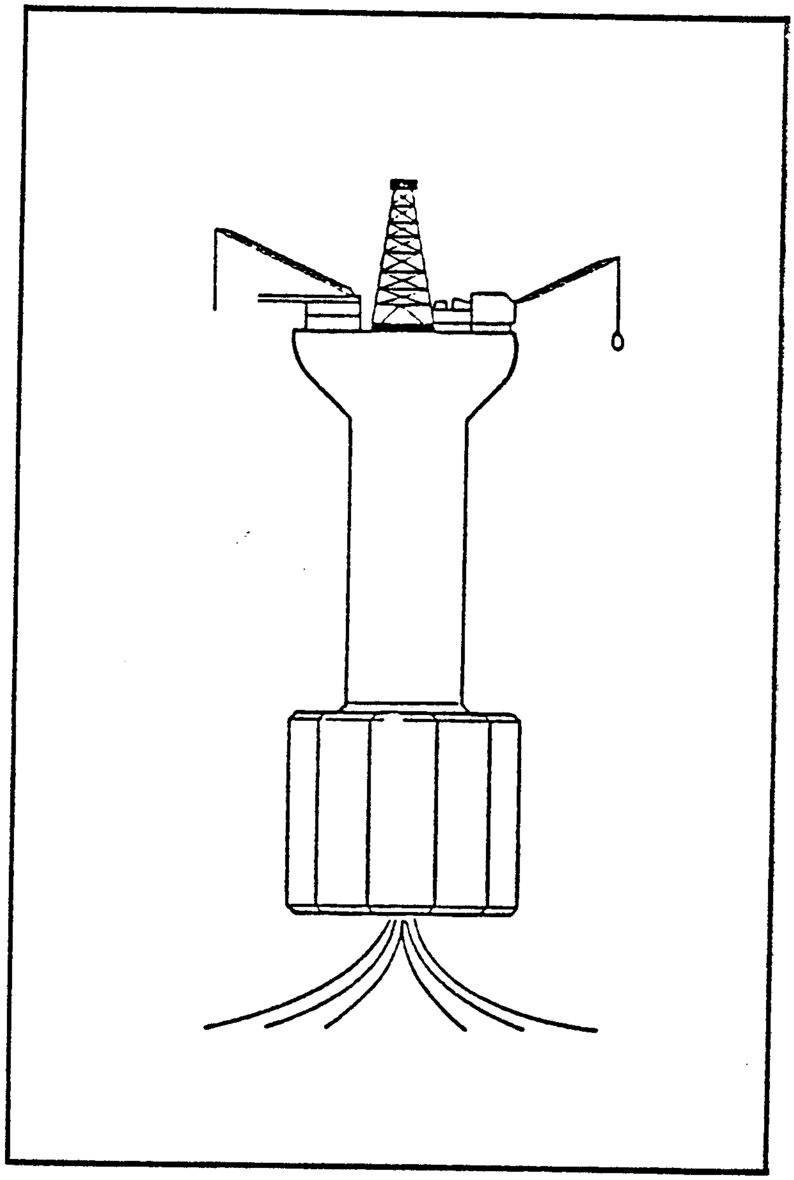
In order to avoid problems of bottom scour and gouging from ice, the pipe will be buried to a depth of 2 meters (7 feet) out to 25 meters of water depth (80 feet) and buried to a depth of 1 meter (3 feet) in the deeper water beyond that. SF/Braun is not planning to pre-trench the line but to trench after pipe laying is completed. Conventional plows or jetting techniques are feasible for this trenching to these burial depths (Timmermans 1982). These depths are assumed based on reasonable tradeoffs of ice gouge risk (Figure 3-8) and costs of trenching in view of the available techniques for burying marine pipelines.

Regardless of the method selected, pipe-laying in arctic offshore regions will require innovations and modifications of existing pipelay techniques. Lay barges with ice-reinforced hulls may be constructed to extend the open-water season somewhat (this will provide only limited extension, say to 10 or 20 percent ice cover, because of the exposed stringer, pipeline and mooring anchor array). Trenching may be completed in the season before the pipe is laid. Pipeline strings may be stored in a trench from previous seasons over winter. A variety of methods will be employed to bring pipes onshore due to the ice scour, ice override, erosion, and permafrost problems at the land-water interface. For example, shallow water approaches and shore approaches will need to be insulated to protect thaw unstable permafrost from the effects of a hot oil line. Gravel causeways may be used for this purpose.

Techniques for construction of land pipelines in arctic areas are well-established and will present no special problems in the Barrow Arch planning area, either for construction of laid pipeline sections to the marine terminal or to an inter-tie with TAPS.

3.3.5 Offshore Loading and Storage

While the extreme remoteness of some Bering Sea and Aleutian OCS areas suggests the use of offshore loading and storage terminals as a feasible



Source: National Petroleum Council 1981

Figure 3-24
ARCTIC FLOATING CAISSON

alternative to the use of pipelines for transporting hydrocarbons to market, present techniques do not appear feasible for fields in the Barrow Arch planning area. Offshore loading systems are not a proven technology for ice-infested areas such as the Chukchi Sea. Offshore loading systems operate best in good to moderate environmental conditions. Systems that have been installed to date in more severe environmental areas such as the North Sea have experienced considerable downtime due to maintenance repairs and severe sea states.

Conventional designs for fixed or floating storage, tanker loading-single point moorings (SPM), and combined storage and tanker loading schemes will not be applicable in arctic conditions. Brian Watt Associates have developed a design for an offshore marine terminal in Norton Sound that incorporates 3 to 5 million barrels of storage and is conically shaped to resist ice forces and allows loading tankers to weathervane as required.

The severity of the sea ice conditions in the Chukchi Sea will require loading and storage conceptual designs capable of resisting multi-year pack ice movements. Conical gravity structures or monocones are both capable of providing the required oil storage and ice resistance features that are required. Figure 3-24 illustrates a floating ice-breaking moored caisson vessel proposed as a production platform in water depths beyond 300 meters (1,000 feet). It incorporates an hour-glass shape at the waterline with downward breaking cone surfaces to fail ice. The structure was sized for a production rate of 100,000 barrels per day and 500,000 barrels of oil storage (Knecht et al. 1979). Such a structure would not be applicable to the Chukchi Sea, without adaptation of the general concept to bottom-founded support in shallow water.

Fixed pile or gravity base loading/storage towers have also been presented as options for less severe ice environments than those found in the Chukchi Sea. Designs of such structures for the Barrow Arch area would have to be greatly increased in size and weight to resist moving ice. Concrete structures would be more desirable due to their greatly increased weight to resist sliding and overturning. Modification of tower designs will be required to protect mooring and hose handling equipment. The height of the tower above the ice surface should be sufficient to avoid rubble pile interference with equipment.

Articulated column or tower designs have also been examined for their applicability in ice environments. Again, significant modifications of conventional designs would be required. Also, as discussed in early production systems, several designs for arctic moored ice-breaking tanker or barge loading designs have been developed.

In the Barrow Arch planning area, large reserves plus sustained high production rate will be needed to justify the large cost of development. A fleet of ice-breaking shuttle tankers would also be required. A large amount of offshore storage will be required in the form of storage vessel facilities. In order for the system to be economic, the throughput (e.g., 300,000 barrels per day loaded into shuttle tankers) would have to be dependable and substantial. This is a challenging operation due to ice movement and severe winter weather conditions.

Although the costs of conventional offshore loading systems appear to be much less than the cost of long pipelines, there are additional costs to consider. These costs include extra storage, a fleet of shuttle tankers, work boats, and possibly ice breakers, hiring of crews, and the construction and maintenance of shore facilities. In Alaska, offshore loading does not necessarily eliminate the costs of a shore terminal since purpose-built arctic icebreaker shuttle tankers would likely offload their cargoes at an Aleutian transshipment facility where the crude would be transferred to large tankers destined for markets to the south.

Arctic offshore storage and loading systems have not been developed, but general concepts have been proposed. For year-round operation, whatever designs prove out for the future, the facilities must be very large to accommodate storage volumes, ice-breaking tanker operations, and the resultant massive ice forces. The APLA concept (described in Section 3.3.2.4) includes these characteristics and so appears potentially feasible technically, assuming availablity of construction material sources and the "super dredges" described. We have used this concept for our economic analysis because it is the best-described arctic offshore storage and loading scheme available at this writing. Other concepts for arctic offshore storage/loading that could be applicable to the Chukchi conditions and timing can be expected in the near future.

3.3.6 Subsea Completions

Subsea technology has evolved in response to the increasing water depths and cost of fixed platform production systems. Theoretically, a subsea production system can either be an adjunct in a field development strategy involving fixed platforms or a complete production system. As a complete system, subsea trees, gathering manifolds, control systems and flowlines are used in conjunction with a floating processing and storage facility. Subsea gas-oil separation and storage is technically feasible but is less likely to be implemented because of cost and complexities.

The principal design problems in subsea production systems are maintenance and operation. In the design of subsea wells, two principal concepts have been employed -- "wet" Christmas trees and "dry" Christmas trees. The wet Christmas tree exposes all the components and requires divers for installation and maintenance. Typically, the wet Christmas tree is completely assembled and tested before installation on the sea floor from a drilling rig. The dry Christmas tree is totally enclosed in a chamber and can be serviced by men working in an atmospheric environment on the sea floor. A number of subsea production systems have been developed including those by Exxon, Lockheed, Deep Oil Technology, Subsea Equipment Associates Ltd. (SEAL), Cameron Iron Works, Regan Offshore International and Vetco. These systems variously employ single wellhead completions, multiple well templates, and combinations of "wet" and "dry" subsea equipment.

The advantages of subsea production systems include (Ocean Industry 1978):

- Early production can be established. Fabrication, installation of a fixed platform, and development drilling can take 5 years or more, whereas subsea equipment can be fabricated and installed in 1 to 2 years. This not only enables an early cash flow, but also permits evaluation of the reservoir prior to investment in permanent structures and equipment.

- Exploratory and delineation wells, which are normally plugged and abandoned, can be turned into satellite subsea producers.

- Subsea production equipment, in contrast to platforms, can be inexpensively salvaged after production diminishes below economic limits.

- Fields with insufficient reserves to justify investment in fixed platforms can be developed relatively inexpensively (especially if exploration/delineation wells can be utilized) by a subsea system with a temporary floating rig or jackup platform.

- In the case of shallow or complex reservoirs, subsea wells can drain those parts of the reservoir that cannot be reached by directional drilling from a fixed platform. Also, subsea wells can be used as injection wells for secondary recovery operations.

- Subsea systems extend production into water depths beyond the limits of platforms.

- Subsea systems can be used in arctic regions (below ice gouging) where surface structures are exposed to the potentially damaging forces of sea ice.

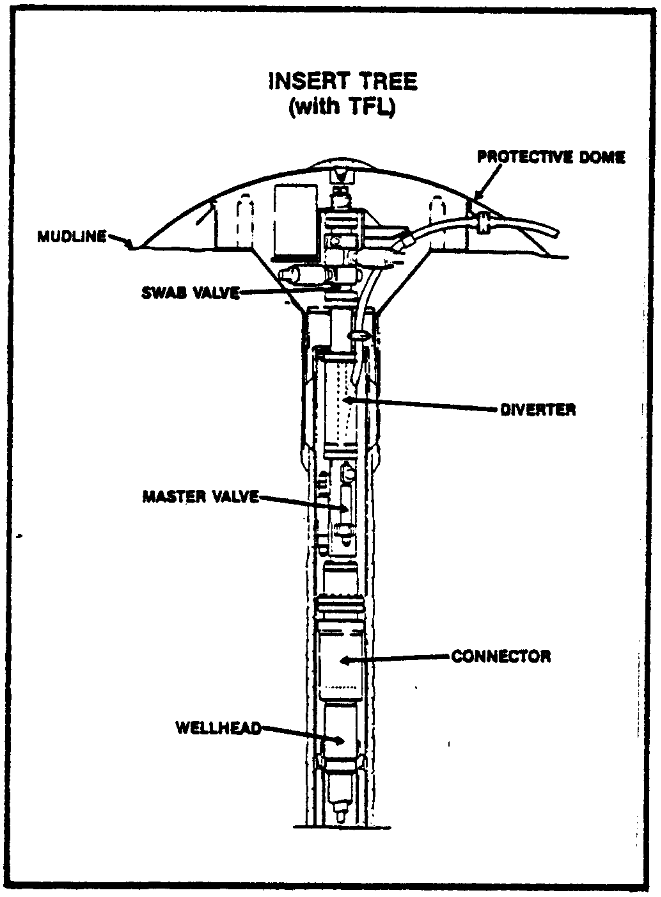
- In areas of incompetent sea floors unable to support bottom founded structures, subsea systems may provide a solution.

Complete subsea production systems are not yet considered state-of-the-art. However, subsea satellite wellheads, with pipelines to a mother platform, do appear to be feasible with shallow/low production reservoirs. Increasingly, operators are developing experience with and relying on sea floor wells. However, the evolution of sea floor well technology has been a slow process and most industry attention is currently focused on subsea production systems for deep water as opposed to arctic or sub-arctic installations (Mason 1980).

Clearly, subsea production systems offer substantial benefits in hostile environments such as the Chukchi Sea. Their cost is a fraction of what full-scale arctic-designed platforms would cost. The only subsea system installed in arctic waters to date is a subsea blow-out preventor (BOP) and production Christmas tree developed for Panarctic Oils Ltd. for gas drilling in the Drake Point Field of the Canadian arctic islands (Energy Interface Associates 1979). Cost was approximately $5 million. However, ice conditions at this deepwater site within the Canadian arctic islands are considerably less severe than those in the shallow Chukchi Sea.

To avoid the hazard of ice scouring, which is common in the Chukchi Sea into water depths of approximately 60 meters (200 feet), a BOP or Christmas tree has to be placed below the mudline and either protected within a caisson or buried in a "glory hole" at a depth dictated by the size of observed scour (Energy Interface Associates 1979). Figure 3-25 shows a recently developed subsea tree installed below the mudline. Only the swab valves, tree cap and flowline connector extend above the seafloor. In arctic offshore applications, the top of the protective dome would be placed below the scour depth and the flowlines would also be buried.

Before subsea production systems or subsea components for oil or gas wells receive widespread usage in arctic environments, high reliability and diverless maintenance will have to be proven under actual operating conditions. In addition, the presence of year-round ice cover in the northern pack ice-covered areas of the Chukchi Sea may limit applicability of subsea components.



Source: National Academy of Sciences 1980

Figure 3-25

SUBSEA TREE WITH THROUGH FLOW LINE (TFL) CONTROL

The use of subsea completions in the Barrow Arch planning area will probably be single satellite wells installed below the mudline. These wells would produce through buried flowlines to fixed structures, artificial islands or to shore (Natural Petroleum Council 1981). Economics, not technology, will be the governing factor regarding the applicability of subsea installations.

3.3.7 Arctic Early Production Systems

While existing early production systems have been designed for non-ice environments, several designs for seasonal use in arctic conditions have been suggested. Conceivably, such systems could be used for producing oil during the 5- to 6-month period while permanent production systems are being constructed or installed.

One early production system for arctic summers designed by Swedish shipbuilders Gotaverken Arendal, is based on an ice-strengthened tanker of about 200,000 DWT acting as a storage and production vessel at a submerged single point mooring and subsea well. It would be served by a number of ice-strengthened shuttle tankers using bow loading from the storage ship. Both riser and moorings would be designed for instant release to avoid contact with severe ice.

3.3.8 Marginal Field Development

With the high costs of facilities and equipment (see Appendix B) required to develop oil and gas resources in a remote arctic area such as the Barrow Arch planning area, some significant discoveries will remain undeveloped because they cannot economically justify production. Such "marginal fields" will remain shut-in pending higher oil prices, cost-saving technological advances, or further discoveries close-by with which pipelines and other facilities can be shared. Delayed development of marginal fields has occurred in the North Sea. As noted in a series of articles on marginal fields in Offshore (April, 1978, p. 76):

"The factors which determine whether a field is marginal include the obvious producing characteristics such as reservoir size, shape, and depth below the ground, well producing rates, oil and/or gas quality, and the existence of production problems such as H_2S or CO_2 and sand productions. The status of technology required for development, availability of competent and efficient construction facilities in the area, nearness to market, accessibility for supplies and transport of production to market, plus environmental problems such as earthquakes and hurricanes must also be taken into account."

While the search for more cost-effective engineering solutions to develop marginal fields has been focused on the extension of offshore petroleum development into deeper waters where the cost of fixed platforms rises exponentially with water depth, many of the same principles will eventually be applied to arctic oil and gas development. Some possible solutions and trends in petroleum technology for marginal field development are listed below. While not all of these will be directly applicable to producing marginal fields in the Chukchi Sea, the underlying concepts such as using cheaper, faster and less material-intensive production techniques will be used. The trends and solutions include:

- Use of subsea production systems either as an adjunct to fixed platforms or as part of floating production systems (see Section 3.3.6).

- Two-stage development programs using an early (temporary) production system while further reservoir evaluation assesses the viability of a development plan employing fixed platforms, pipelines and major shore facilities.

- Employment of offshore loading in conjunction with a floating system, subsea system, or fixed platform with storage when long pipelines cannot be economically justified or shared.

3.3.9 Alternative Dredging Approach For Island Construction in the Chukchi Sea

The conditions on the Chukchi Sea suggest use of sea-going hopper dredges or tug/self-loading hopper barge combinations for island building. The exposed nature of the potential sites and the distance to protected areas precludes use of conventional cutterhead pipeline dredges. As used in this report, "hopper dredge" refers to a sea-going, self-contained ship equipped with capabilities to load material through hydraulic pumps to hoppers and to discharge this material by bottom dumping or by pumping ashore to fixed pipeline systems. A tug/self-loading hopper barge has similar capabilities but consists of a tug pushing a hopper barge that has the capability to load through hydraulic pump(s) and drag arms. These dredges are self-powered and have the capability of working in sea heights up to 2 meters (7 feet), riding out storms and transferring material over some distance from borrow area to island construction site. There are approximately 10 sea-going hopper dredges in private ownership in the United States and a limited number of self-loading hopper barges. However, conventional hopper barges can be converted to self-loading barges by addition of "off-the-shelf" equipment.

In order to prepare a comparative cost estimate, the following assumptions were made:

- Size of an Exploration Island: 1.7 million cubic meters (2.2 million cubic yards) of which 1.3 million cubic meters (1.7 million cubic yards) is below 23 meters (75 feet) and 382,300 cubic meters (0.5 million cubic yards) above.
- Dredging Depth for Borrow: maximum 15 meters (50 feet).
- Average Haul Distance from Borrow Area to Island: less than 16 kilometers (10 miles), greater than 8 kilometers (5 miles).
- Material: Sand with some gravel less than 0.6 centimeters (1/4 inch).
- Working Season: 75 working days, more or less.

The hopper dredges would mobilize to the site at the start of the working season. Both dredges would begin hauling material from the borrow site and bottom dump at the island location, bringing the center of the island up to about 7 meters (23 feet) of depth. After one month, a self-elevating platform and mooring barge would be mobilized and put in place on the lee side of the island in approximately 9 meters (30 feet) of water. The platform would be used to secure the mooring barge and provide the stable connections for the underwater pipe leading from it to the center of the island. A smaller end barge would be used to secure the island end of the pipe and bring it to the surface for discharging and eventually landing the pipe to the island.

One dredge would begin to haul material and pump out to the island via the pipeline after being secured to the mooring barge. The other dredge would continue to bottom dump, building up the submerged periphery of the island.

When the center of the island breaks the water surface, both dredges would pump ashore until the island was well established. They could then pump ashore or bottom dump, depending on the quantity distribution to complete the island.

Based on the above operation concept, the following equipment spread is suggested based on fuel arriving by contract fuel barging service.

- o Two sea-going hopper dredges with minimum hopper capacity of 2,300 cubic meters (3,000 cubic yards) of sand and capable of pumping material from the hopper ashore.
- o One Delong-type self-elevating platform suitable for mooring in up to 15 meters (50 feet) of water and equipped with workshops, quarters and storage areas.
- o One mooring barge approximately 76 meters (250 feet) long equipped with anchors and winches suitable for independent moorage or moorage along side the platform.

- One derrick barge and two tugs.

- Two caterpillar tractors.

- Pipeline, connections and end barge all in duplicate for pump ashore operation.

While it is believed the tug-barge combination would be suitable for this work, sea-going hopper dredges have been used as the basis for cost estimating purposes.

This approach to dredging and filling an artificial island shows potential for significant cost savings, as well as greater operational flexibility, compared to the cutter-head dredges assumed for our economic analysis and described in Section 3.3.1. It appears that the fill placement costs with this approach could be less than half the costs assumed in our analysis. This savings would apply to the major cost of fill island construction -- dredging -- but would not necessarily result in savings for slope protection and equipment installation, although the latter operations may prove less expensive too with this dredging approach.

3.4 Production Conditions and Field Development Strategies for the Barrow Arch Planning Area

This section briefly reviews some of the principal criteria influencing an operator's selection of a field development plan in the Chukchi Sea and discusses our selection of the production systems and development issues evaluated in the economic analysis.

A number of factors influence an operator's decision on the production and transportation strategies to be used in field development. These include: field size, reservoir and production characteristics, physical properties and quality of oil or gas, location of the field, distance to shore, distance to other fields, oceanographic conditions, destination of production, availability of existing terminals, and economics.

3.4.1 Field Size

The economic analysis (see Section 6.0) suggests the necessary reserve size thresholds to justify production under alternative production systems including piping production to onshore terminals for transfer to ice-breaking tankers, pipelining production east to TAPS, and offshore loading directly into tankers from an arctic production and loading atoll (APLA). It is assumed that a giant field must be discovered in the Chukchi Sea to initiate petroleum development.

3.4.2 Reservoir and Production Characteristics

Reservoir and production characteristics are major determinants of transportation (pipeline capacity, storage) and platform equipment requirements. A field development plan will identify the optimal platform requirements, and identify and schedule the development well program, gas and water reinjection wells and rates, and platform equipment processing requirements that are, in part, determined by the transportation option selected. For Barrow Arch planning area, a relatively high production rate has been assumed because of the need for favorable economics to initiate development; this rate was selected based upon our review of the petroleum geology as being optimistic but entirely possible.

3.4.3 Quality and Physical Properties of Oil and Gas

The characteristics of oil produced from Barrow Arch will have a significant influence on the feasibility and economics of the selected transportation system. Important crude properties to be considered in the design of a transportation system (pipeline and/or tanker) include:

- Viscosity -- This dictates how well the oil will flow at a given temperature. Variations in viscosity will influence the pumping power required in pipeline transport. Cooling of oil in pipeline transport may lead to wax build-up in the pipeline and reduce effective pipeline diameter. For a waxy crude, direct loading to a tanker may be favored over pipeline transport.

- Salt water -- A small percentage of water is still present in the crude oil after primary separation on the platform. It is costly to separate the water from the oil, and it is even more costly to separate residual oil from water so that it can be discharged offshore. It is also economically unattractive to transport salt water with the crude because of pipe corrosion and reduced oil capacity, although removal of the water onshore may be less expensive than offshore.

- Sulphur -- Sulphur or hydrogen sulphide is a contaminant that, if left in the crude, can cause rapid deterioration to steel pipelines.

These and other factors influence pipeline and processing equipment design. There are trade-offs between the cost advantages of onshore crude stabilization and processing, and the upgrading requirements for offshore platform processing equipment for pipeline transport to shore.

Gas produced in association with the oil can either be transported to shore by pipeline or reinjected into the reservoir. If the crude is produced directly to tankers, associated gas could be reinjected or flared. Some will be used as platform fuel. Gas reinjection equipment is a major cost component. Reinjected gas can be marketed later as economic circumstances change. Associated gas may be reinjected into the reservoir to maintain pressure and to prolong the life of the field. Further, reinjection of associated gas is the only viable solution to the flaring ban imposed upon producing fields if natural gas production is not economically feasible.

As the gas-oil ratio increases, the size of the pressure or production vessels and pipelines increases. Large and more sophisticated equipment is required to handle the gas. At some point, depending on the amount of gas and entrained liquids handled, and on costs, the natural gas liquids will be stabilized and injected into the oil pipeline.

On offshore platforms, space requirements for larger process vessels, pipelines, and the increased equipment requirements for gas processing are usually not great enough to significantly affect the platform costs. Natural gas pipelines are usually trunklines as large quantities of gas reserves are required to produce sufficient revenue to pay back the capital investment (even without a return on the capital).

According to the assessments of the National Petroleum Council (1981), the Barrow Arch planning area shows potential for large gas fields. LNG technology will probably have to play a role in bringing Barrow Arch gas to market. The question of what and where the markets are for LNG will influence the economics of gas trunk pipelines to shore and onshore LNG production. The feasibility of arctic LNG production will be established by the Arctic Pilot Project, an undertaking of Petro-Canada, Dome Petroleum and others to bring gas from the Drake Point Field off Melville Island in the Canadian Beaufort Sea 160 kilometers (100 miles) by pipeline to a bargemounted LNG plant and storage tanks for shipment by ice-breaking LNG tankers. If regulatory approval for the project is received by early 1983, delivery of arctic gas could begin as early as 1986 or early 1987 (personal communication, Sandy Hunter, Petro-Canada, 1982).

3.4.4 Distance to Shore

Other factors being equal, the closer a field is to shore the more likely that production will be transported to shore by pipeline than by tanker. The unit transportation costs for oil increase with greater pipe length, whereas the transportation cost per barrel in an offshore loading system is relatively insensitive to modest increases in water depth. However, the ultimate destination of the crude and the number of terminal handlings are also important considerations.

It is also important to note that the feasibility of offshore loading concepts in arctic regions have not been proven and that longer pipelines may be more economic in the Arctic due to the high cost of arctic offshore loading concepts.

3.4.5 Meteorological and Environmental Conditions

Because information on sea ice in the Chukchi Sea is very limited, the ice forces estimated and platform designs postulated are tentative. Nevertheless, sea ice will be the most significant factor in selecting production systems, from platforms to transportation concepts. It will also be a major factor to overcome in establishing the feasibility of year-round exploration operations and resupply logistics. Ice-breaker support will be required for all marine activities.

Platforms will have to be installed or constructed during brief open-water seasons and all concepts must be capable of surviving the movement of multi-year pack ice. Artificial islands, in addition to passive defense measures, may need to maintain active defense activities when severe ice events occur. All mobile exploration vessels or platforms used on a year-round basis must be capable of surviving in multi-year pack ice conditions and should be able to rapidly disconnect and move off-station to avoid ice islands if necessary.

The onshore terminal for crude oil must be capable of operating year-round, regardless of the weather and of the ice conditions. This requires that the offshore single-point mooring (SPM) or tower must be capable of withstanding the impact of pack ice, and of breaking that ice to protect moored tankers. It must also be capable of monitoring, directing and controlling the movement of tankers in the vicinity of the terminal to permit safe mooring and departure in adverse weather. Means for attaching mooring lines and cargo piping in periods of sub-zero weather, high winds and low visibility must be provided.

Ice-breaking tankers, ice-breaking supply vessels and other craft intended for other than seasonal open-water operations must have hull designs capable of resisting ice impact with minimum chance of holing. Double-hull features, segregated ballast tanks and advanced satellite-based navigation aids will all be required.

The presence of seasonal ice cover and ice scour will require that all pipelines be trenched below ice scour depth and installed during open-water season. All pipeline construction and most installation activities will also take place during the short open-water season.

The Barrow Arch planning area's meteorology will also impose operational problems. While superstructure icing will not be a major problem, extremely low air temperatures will be. Severe cold reduces worker productivity, constrains many operational activities and requires use of special cold-resistant metals and materials. Low visibility due to darkness, fog and storms will also pose a significant constraint to operations. Storm winds may be intense, and although waves will only be a problem during the open-water season, the concentration of operations during this time period leaves little leeway for rescheduling.

Offshore loading systems are untested in arctic regions, and while weather and maintenance/repair downtime ratios have been established for such systems in the North Sea, design and operation of systems for ice-infested areas of the Arctic present more severe constraints. Design of offshore storage facilities has to match production rates, frequency and size of tankers, and expected weather and SPM maintenance downtime. Furthermore, the storage and loading system must allow for very high pumping rates when a tanker is available to load. Lack of operational experience with such systems in the Arctic also limits our ability to predict repair and maintenance requirements, which are likely to be high due to ice forces and severe cold. Provision of adequate storage for unexpected tanker delays will be required to ensure continuous field production with technical and cost constraints on the maximum amount of storage that could be provided on an APLA or other ice-designed storage structure; there may still be times when production will have to be curtailed.

3.4.6 Location of Terminals

Virtually all Barrow Arch crude will be exported to the Lower 48. A very small amount may be refined in Alaska at Kenai Peninsula plants. One or more onshore pipeline terminals will serve as transshipment facilities. The terminal(s) will stabilize the crude, recover liquid petroleum gas (LPG), treat tanker ballast, and provide storage for about 10 to 15 days' production. The most logical location for a terminal to serve oil fields in the northern part of the Barrow Arch planning area would be in the vicinity of Point Belcher near Wainwright where deep water approaches relatively close to shore. In fact, a terminal at Point Belcher may already be in existence by the time Barrow Arch fields are developed. A terminal located at Point Belcher could also serve finds in the western section of the Diapir Field planning area that may be leased before Barrow Arch development takes place. Similarly, production from finds located in the western portions of the National Petroleum Reserve-Alaska (NPR-A) may be shipped via tankers from Point Belcher.

For finds in the southern part of the Barrow Arch planning area, the lack of good deep water anchorages in Ledyard Bay might make location of a terminal south of the Lisburne Peninsula in the vicinity of Cape Thompson a possibility. Oil would be shipped south from a terminal at either Point Belcher or Cape Thompson in ice-breaking tankers to an Aleutian Island transshipment terminal that could also serve fields in other Bering Sea lease sale areas, such as the St. George Basin, North Aleutian Shelf, and Norton Sound areas. In fact, the Aleutian Islands and southwestern tip of the Alaska Peninsula are strategically placed for support and transshipment functions for most of the Bering Sea and Chukchi Sea basins. Crude oil from Barrow Arch offshore fields will be transferred to larger tankers destined for the U.S. westcoast at the terminal in the Aleutians.

3.4.7 Barrow Arch Production Strategies Selected for Economic Analysis -- Summary

The geography and environment of the Barrow Arch planning area offer few options in development strategies. Further, these same factors imply that only the find of a major field would provide a viable economic investment. The petroleum geology does in fact hold out prospects for giant fields (see Appendix A-II). We have assumed that the initial development of the Chukchi Sea, like the North Slope, will require a major find to justify the risks of starting the petroleum technology infrastructure needed to bring Barrow Arch hydrocarbons to market.

The major alternative strategies for Barrow Arch petroleum development are four:

- Relatively short marine pipelines or combination marine-land pipelines from producing platforms to shore; construction of an onshore crude oil terminal with storage and facilities for loading a fleet of ice-breaker tankers; an Aleutian transshipment terminal for very large crude carriers (VLCC's) carrying crude to market.

- Relatively short marine pipelines to shore; construction of an overland pipeline approximately 500 kilometers (300 miles) east across the North Slope for transfer to the trans-Alaska pipeline system (TAPS); transfer of crude into VLCC's to market at Valdez.

- Offshore treatment and storage of field production at a facility such as an APLA; loading into a fleet of ice-breaker tankers; an Aleutian transshipment terminal for VLCC's carrying crude to market.

- Pipeline production southward to a new loading terminal on the west coast of Alaska.

Strategies 1 and 3 may require a lower threshold of reserves to begin production since oil movement by tanker is considerably more flexible than by pipeline. However, the capital costs associated with construction of an ice-breaking tanker fleet are high and year-round operation of a high-arctic marine terminal will present many difficulties due to sea ice and weather. Although this strategy will require an Aleutian transshipment terminal, a reasonable presumption is that such a facility might already exist to service Bering Sea production. This could help offset the capital and operating costs for this strategy's second terminal.

Strategy 2 has the advantage of tying into the already proven TAPS, but oil pumped through the line will have to bear the TAPS tariff, which is considerable. Also, the costs of the new connecting pipeline will be high. However, this strategy eliminates the expense of constructing and operating an ice-breaking tanker fleet and two terminals.

For strategy 4, we examined a scenario including pipelining oil or gas from a southern Barrow Arch field to a new terminal on the south side of the Lisburne peninsula. This and related strategies, such as land pipelines to Nome, require trading off long onshore pipelines to gain some reduction in the environment for a loading terminal and ship operations.

4.0 PETROLEUM FACILITIES ONSHORE SITING

4.1 Overview of Onshore Facilities

Siting of onshore facilities is an important element in oil and gas development in the Barrow Arch planning area. Oil and gas development always requires a suitable complement of onshore facilities, and development of such facilities along the northwest coast of Alaska will be a challenge, not only due to the severe weather and ice conditions prevailing during most of the year, but also because the existing physical infrastructure in the area is so limited. The effort required will be analogous to establishment of the Prudhoe Bay facilities.

Transportation distances to habitable living areas and supply base sites are much greater in northwest Alaska than in comparable offshore fields in other parts of Alaska with the exception of the Navarin Basin. Long distances and severe weather will make ready transport difficult. Personnel will be required to live on location for longer periods, requiring recreation and medical facilities. Critical supplies and spare parts must be stored on-site.

At present the northwest coast of Alaska in the Barrow Arch planning area offers only limited potential to support the marine and onshore activities necessary for oil and gas exploration and development. With the exception of Barrow, which has a population of nearly 3,000, the other established communities, Umiat and Nuiqsut, are extremely small and poorly equipped to support oil and gas industry operations. All are isolated by lack of overland transportation and lack of marine transportation in the winter. While a few small airstrips exist along the coast, any would require expansion or modernization to handle anticipated air activities associated with oil and gas development. Ship transport is limited by the absence of adequate port facilities and the shallow water depths throughout the area. Barge unloading sites presently exist only at Barrow and Peard Bay.

The actual onshore facilities required to support oil and gas development will depend greatly on the magnitude of offshore fields, their location, whether oil and gas or only oil is actually produced, and the transportation systems selected to service field production. For the purposes of this report, a representative range of required onshore support facilities is presented. As exploration and development actually proceeds in the Barrow Arch planning area, more detailed studies of possible support bases, terminal sites, and pipeline routes will need to be conducted.

4.2 Physical Environment of the Region

The arctic coastal plain is a smooth surface rising gently from the shore of the Chukchi Sea to a maximum height of 180 meters (600 feet) at its southern end. Due to the extensive flat terrain and the continuous occurrence of permafrost under a shallow active layer, drainage on the coastal plain is very poor, and marshes occur in low places. Rivers that cross the plain originate in the hills or mountains to the south.

In the western part of the region, the plain is covered by thaw lakes that have their long axes aligned north-northwest and cover 50 percent of the land. The lakes range from several meters to over 30 kilometers (20 miles) in length and are seldom deeper than about 3 meters (10 feet). The lakes form, enlarge, and drain continually.

The entire land area is underlain by continuous permafrost extending from a few centimeters below land surface to depths ranging from 200 to 600 meters (600 to 2,000 feet).

The Chukchi Sea coast is fronted at most places by narrow gravel beaches below low coastal banks and bluffs. From Cape Lisburne to Cape Thompson, high rocky sea cliffs drop abruptly into the sea for several hundred meters.

Chains of barrier islands extend for many kilometers parallel to the coastline, enclosing shallow lagoons with numerous shoals. This occurs from

Point Lay to Wainwright where the enclosed Kasegaluk Lagoon provides a protected waterway for well over 160 kilometers (100 miles), reaching past Icy Cape almost to Wainwright. This section of coast ends at Peard Bay and from that place to Barrow the coast has been undercut to form prominent cliffs.

4.2.1 Sand and Gravel Resources

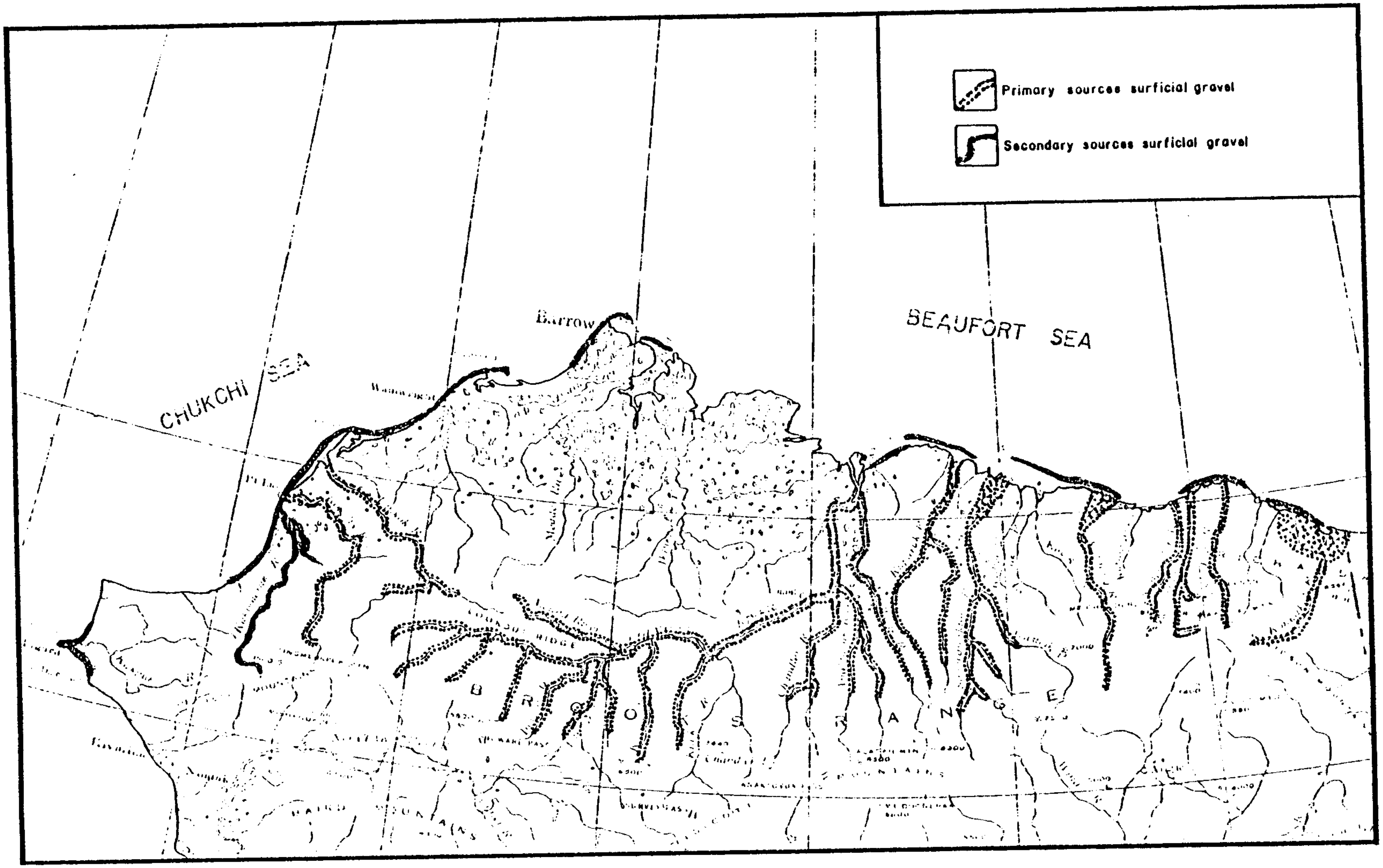
Sand and gravel sources will be critical to construction of onshore facilities in the Barrow Arch planning area. Figure 4-1 illustrates the distribution of surficial gravel deposits in the Barrow Arch planning area and Figure 4-2 shows bottom sediment types in the vicinity of the southern portion of the Barrow Arch planning area.

4.2.2 Freshwater Sources

Supplies of fresh water to service onshore facilities in the Barrow Arch planning area are not well delineated. Little data is available on the extent of surface water available during winter months. According to Rick Smith of Alaska's Department of Natural Resources, Land and Water Management Division, water for onshore oil and gas support operations will probably come from sources similar to those used at Prudhoe Bay. The most likely sources for fresh water will be the deep lakes that do not freeze completely to the bottom during winter. It is also likely that some water reservoirs will be created as gravel is extracted from onshore borrow pits. Winter water withdrawals from rivers will probably be restricted to protect fish overwintering habitat.

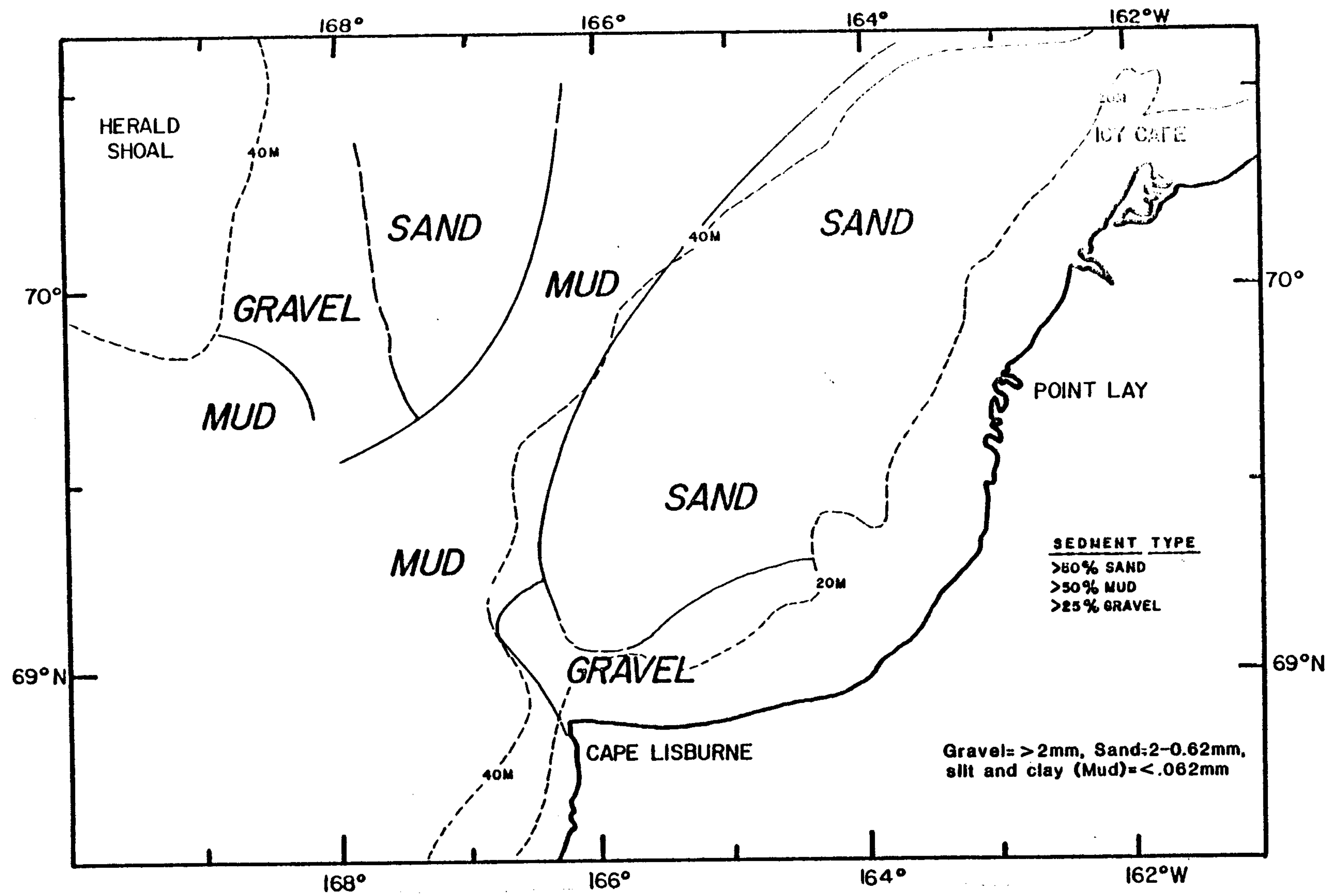
4.3 Types of Onshore Facilities Required

Onshore support facilities will be required at several stages of oil and gas development in the Barrow Arch planning area. The main requirements that must be accommodated in nearshore areas of the Barrow Arch planning area are:



Source: Arctic Institute of North America 1974

Figure 4-1
DISTRIBUTION OF SURFICIAL GRAVEL DEPOSITS



Source: Arctic Institute of North America (1974)

Figure 4-2

CHUKCHI SEA BOTTOM SEDIMENT TYPES

- A basic shore base facility to service exploration, development and long-term production.

- Temporary shore facilities to handle peak construction activities associated with artificial island construction, terminal construction and pipeline construction.

- Appropriate airport or airstrips and heliport facilities to service exploration and development activities.

- A basic port facility to accommodate:
  - service vessels and tugs
  - supply barges
  - construction vessels (dredges, pipelay barges, etc.)
  - ice-breakers for winter port and terminal ice management.

- A marine terminal to receive produced crude oil for treatment, storage and off-loading via a single-point mooring (SPM) to ice-breaking tankers.

- A terminal to liquefy natural gas and transship LNG by ice-breaking tankers.

4.3.1 Marine Service Bases

Marine service bases are an integral part of any offshore development program. Their construction will involve staging areas, operating around the clock to provide drilling materials and support equipment from the coast to the offshore oil fields. Size and function will vary considerably with offshore activity. However, the marine service base will be the longest-lived activity related to offshore development. Marine service bases need to be carefully conceived and efficiently planned so as to aid the stability and economic diversification of northwestern Alaska.

Service bases are required from the time crude oil or natural gas exploration is initiated to the point where production ceases and the equipment is dismantled. The entire range of activities offshore in the exploration and the production of oil and gas resources requires support from onshore facilities.

The marine service base operations must be premised upon taking optimum advantage of suitable weather conditions. Operations should be designed to accommodate peak demands created by adverse weather conditions. The National Petroleum Council (1981) suggests that, in areas like the Chukchi Sea, serious economic studies should be conducted of the possible need for additional capacity in terms of conventional ice-breaking supply boats, work boats, tugs and barges, dock spaces, and other factors to take maximum advantage of favorable weather. Work stoppages that result from not supplying an island-mounted drilling rig or production concept or a pipe-laying barge must be weighed against the increased cost of having a fully manned support base available for use.

4.3.1.1 Exploration-Related Facilities

Depending upon the magnitude of the exploration program and the types of rigs used, base camps could approach the size of a development/production camp, or could be very modest. High investment costs would normally favor a minimal level of development or the use of existing facilities.

Seismic survey or other early exploration efforts will most probably be conducted from self-sufficient vessels with no need for onshore facilities in the area. Onshore support needs will commence with the exploratory drilling phase.

Prior to the start of exploratory drilling, an onshore camp and an operating port must be constructed to house workers and provide storage space and fabrication areas for materials and equipment. If floating rigs are used for exploration drilling, onshore support requirements will be reduced and may not be initially located in the immediate vicinity of the Barrow Arch area. Surveys of gravel and water resources are required prior to construction of facilities and excavation of gravel borrow areas. Transportation facilities to be constructed will include an adequate boat harbor, runways to land fixed-wing supply aircraft and a helipad for cargo and crew helicopters. Appropriate docks and roads will also be constructed to service the harbor and support base complex.

If exploratory drilling in the area is conducted from artificial islands, adequate onshore construction of support base facilities will + require a sophisticated planning and mobilization effort to ensure material delivery prior to the short summer construction season. Although as much work as possible will be conducted off-site to avoid the high costs of labor, low productivity, and weather delays that are inherent in the Arctic, a considerable amount of onshore construction will be required. Onsite activities are likely to include: mining and transporting gravel; filling and grading; construction of roads, workpads, foundations and causeways; and installation of utility distribution systems, prefabricated modules and interconnecting pipework. Care must be taken in all construction activities to minimize the impacts on tundra, waterbodies and wildlife.

Since exploratory drilling in the area is likely to be conducted from artificial islands, adequate space must be incorporated into the base camp to accommodate peak manpower and material loads associated with island construction. Also, because of the severe weather prevailing during most of the year and the criticality of maintaining schedules to complete exploration efforts, ample spares will need to be stockpiled to prevent delays.

Harbor facilities will be required at the outset of the exploratory drilling program. In addition to the need to receive construction loads for shore base fabrication, harbor facilities will be required to service the large amount of marine activity associated with artificial island construction, re-supply and maintenance. Use of floating drilling platforms will greatly reduce this requirement. Although an enclosed barrier island/ lagoon system occurs along much of the lease area's coastline, all of these protected waters are extremely shallow and the entrances are normally not navigable for anything but small boats (Parker 1975). Therefore, due to the lack of suitable natural harbor facilities, a dredged harbor may have to be created.

Because of the need to provide maximum ice protection for over-wintering vessels, a harbor location within an enclosed lagoon appears preferable. However, the amount of dredging required presents several difficulties. Intensive dredging of harbors and harbor entrances could cause major erosion of both onshore and offshore permafrost. There are no currently accepted methods of stabilizing underwater permafrost and the costs of stabilizing even small areas where the permafrost must be penetrated (as in drilling oil wells) has proven to be quite high. The accepted method of insulation used in building roads and airstrips is to put a blanket of gravel or other material over the permafrost. If this method is used in constructing harbors, it means that very large amounts of material will have to be used to extend the landmass into deeper water rather than dredging into the land. There may be sites where this is possible along the northwest coast of Alaska but they have not been identified as yet (Parker 1975). Also, many waters of the Chukchi Sea are poorly charted and intensive bathymetric survey work will be required prior to harbor construction.

If an enclosed lagoon cannot be utilized for a harbor site, a dredged harbor may be created some distance from shore, due to the shallow water depths found in the Chukchi Sea. The offshore harbor would be dredged one to several kilometers offshore, surrounded with a protective berm, and connected to the shore by a gravel causeway.

Since promising areas of the Barrow Arch planning area are more than 500 nautical miles from a major deepwater port, supplies and equipment will be most economically moved by barge. Although barge operations are presently confined to the open-water season, the construction of ice-breaker barges could make year-round resupply possible. Even prior to harbor dredging, landing craft-type barges could deliver supplies directly to a beach or a temporary cargo pier.

At a minimum, the harbor should have the physical dimensions to allow maneuvering, anchoring and berthing of a large enough number of supply boats, barges and other vessels supplying the base. A minimum of 10 to 12 hectares (25 to 30 acres) dredged to 10 meters (30 feet) would be required. Ideally, it should have the dimensions to accommodate a number of vessels that may be forced to call to port for emergency repairs or seek refuge from storms.

The harbor must be deep enough at dockside to accommodate supply boats and barges to load or unload all various items of cargo necessary to support an offshore operation. The supply boats must operate around the clock throughout the year taking into account the range of possible ocean and ice conditions. During the exploration and construction phases, they may also be used to haul anchors in support of pipelaying, and operate other support missions from towed rigs or platforms.

Berthing space is an important parameter to harbor capacity. It is essential to be able to load many supply vessels in a relatively short period of time and space must be available to carry out this function.

The siting of the supply base within the harbor is also important. Since service base operations are predicated upon taking optimum advantage of suitable weather conditions, their efficiency is measured in terms of turn-around time. To do this, vessels must be able to move to and from the service base with as little impediment as possible.

4.3.1.2 Production-Related Facilities

Facilities required in support of field development and production operations will be significantly greater and more permanent than those required for exploration. The exploration base camp could be expanded to accommodate development and production, or a new marine production support base could be constructed in closer proximity to the actual offshore development fields. The major activities to be serviced by the marine service base in the post-exploration period are:

- Construction
- Development
- Production
- Post-Production

Construction

The construction stage involves constructing production islands or expanding exploration islands into production islands, installing towed production concepts, building oil collection stations or gas processing plants and tanker terminals, and laying of trunk and feeder marine pipelines to shore and land pipelines to a terminal or pump stations. A marine service base plays an active role in support of installation of production concepts through its support of tugs, barges and other vessels required to install the platforms, pipelines, and production equipment. This generally does not involve a large tonnage or volume of material except in support of pipelaying operations where a large volume of pipe may have to be stored and distributed.

Development

The development stage consists of drilling numerous deviated wells from the production platforms. Generally this phase represents the height of service base activity in terms of tonnages and volumes supplied offshore.

Production

Production commences with the flow of oil or gas and continues through the life of the field. The volume and tonnage supplied offshore are substantially reduced. Also, operations and manpower requirements are reduced at the shore station.

Post-Production

After the fields are exhausted, the service base may support the dismantling of production platforms and other offshore facilities.

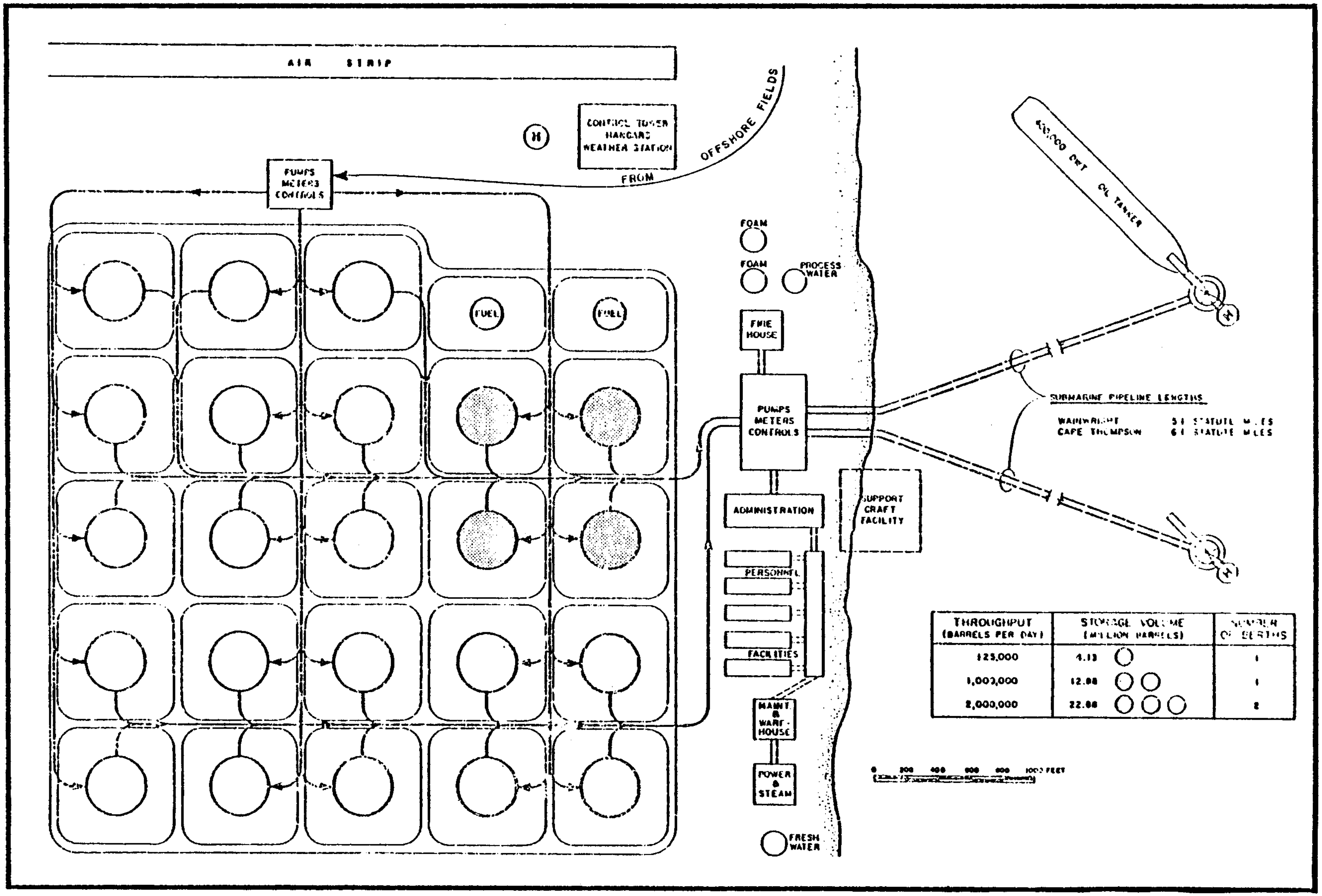
Incorporated as part of the marine service base should be several types of facilities in addition to the harbor and crew quarters and mess. The physical plant is likely to include: a pipe marshalling or terminal yard; warehousing for tubular drilling goods and drilling muds and cements; storage tanks for chemicals, fuel and water; fabrication yards; communications facilities; office accommodations; mud and cement make-up facilities; vehicle and machinery maintenance and repair shops; power plant; sewage facilities; and oil spill response and clean-up equipment.

4.3.2 Marine Terminal

In addition to the marine service base, a marine terminal to receive, treat, store, and transfer crude oil to ice-breaking tankers may be constructed. Conceptual designs for such arctic facilities have been developed by Global Marine (1978), Bechtel (1979), and McMullen (1980). In addition, several proprietary studies of arctic marine terminals have been prepared for industry operators.

The onshore facilities associated with a marine terminal include storage tanks, a topping plant, a power plant, a tubular and equipment yard, a warehouse, and storage areas and shops. Figure 4-3 illustrates the layout of such a facility. The terminal will be connected to the offshore fields by marine pipelines and to two SPM structures, each located in deep water at the end of a several kilometer marine pipelines and capable of off-loading into ice-breaking tankers.

To achieve maximum efficiency in utilization of harbor facilities, labor, equipment and onshore facilities, the marine terminal will probably be located in close proximity to the marine service base, except in the event that oil is found in the southern end of the Barrow Arch planning area. In such a case, marine service base facilities would be located in Ledyard Bay while oil would be transported ashore via pipeline and transported overland across the Lisburne Peninsula by pipeline to a marine terminal in the vicinity of Cape Thompson.



Source: McMullen 1980

Figure 4-3
CRUDE OIL MARINE TERMINAL

4.3.3 Pipeline Service Requirements

In the event that oil or natural gas is transported east via pipeline to the Kuparuk pump station instead of being transported to a marine terminal for transfer to ice-breaking tankers, some additional onshore facilities will be required. Pump stations or compressor stations would have to be constructed to boost the flow of produced hydrocarbons.

4.3.4 Natural Gas Liquefaction Plants and Terminals

In the event that a pipeline is not constructed to transport natural gas, a liquefaction plant and marine terminal would be constructed to liquefy natural gas, store the produced LNG and transfer it to ice-breaking LNG tankers at an SPM. The Arctic Pilot Project being undertaken by PetroCanada to produce Mackenzie Delta natural gas is one such project. Figure 4-4 illustrates the likely layout of such a facility.

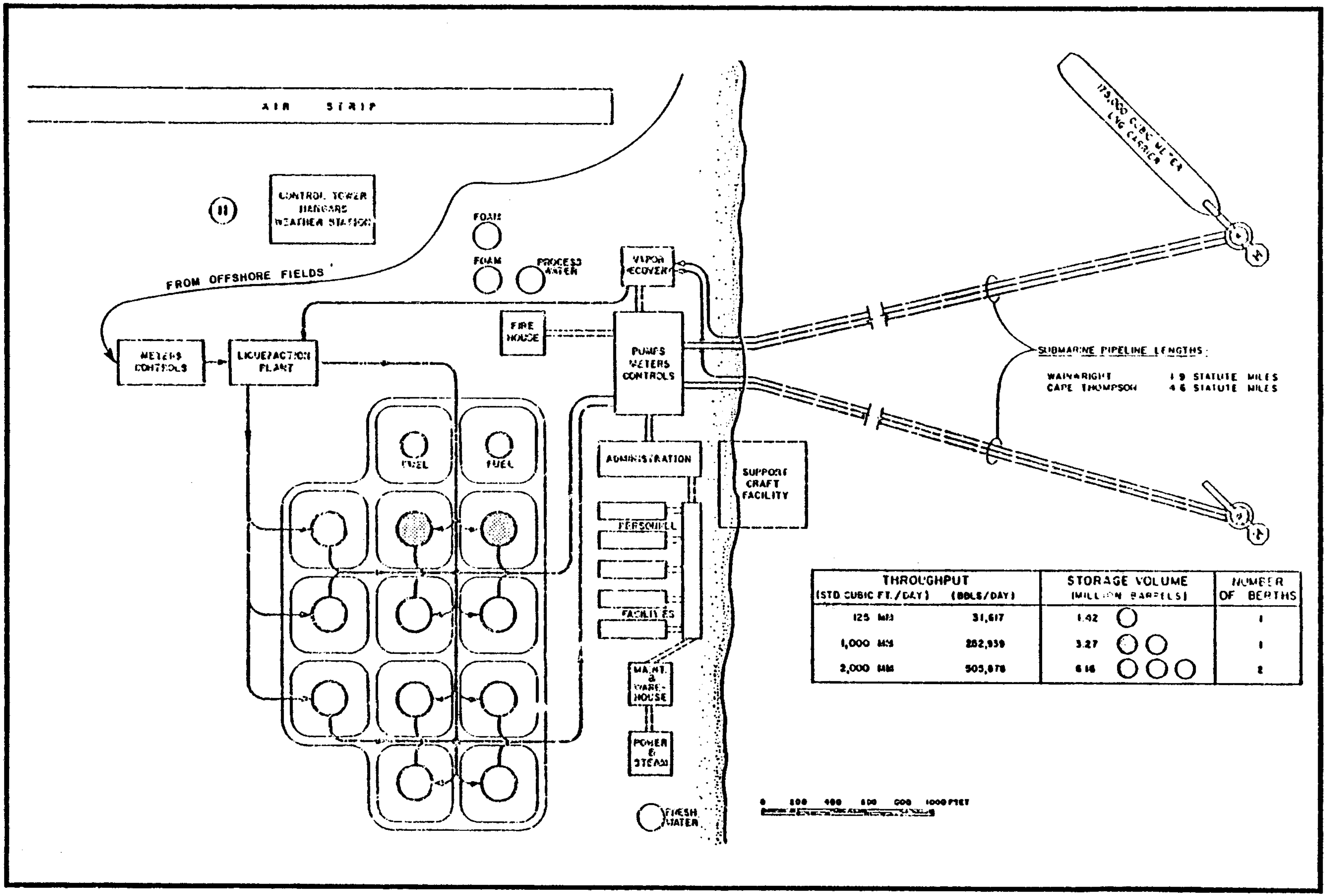
4.3.5 Summary of Petroleum Facility Siting Requirements

Table 4-1 illustrates some representative siting requirements for the major onshore facilities required to develop the oil and gas resources of the Chukchi Sea. Figure 4-5 illustrates how such representative facilities might be arranged.

4.4 Onshore Facilities Siting Constraints and Criteria

A variety of technical and environmental constraints and criteria must be taken into account selecting sites for onshore oil and gas facilities. Among the constraints to be considered in selecting onshore sites for support facilities are the following:

- Landfast ice
- High rates of coastal erosion
- Nearshore permafrost



THROUGHPUT (STD CUBIC FT./DAY)	(BBLS/DAY)	STORAGE VOLUME (MILLION BARRELS)	NUMBER OF BERTHS
125 MM	31,617	1.42	1
1,000 MM	252,939	3.27	1
2,000 MM	505,878	6.16	2

Source: McMullen 1980

Figure 4-4

LIQUEFACTION PLANT & LNG MARINE TERMINAL

TABLE 4-1

SUMMARY OF PETROLEUM FACILITY SITING REQUIREMENTS

Facility	Land Hectares (Acres)	Harbor Entrance	Channel	Turning Basin	Berthing Area	No. of Jetties/ Berths	Jetty/ Dock Frontage Meters (Feet)	Minimum Turning Basin Width Meters (Feet)	Comments
Crude Oil Terminal									
Small-Medium (<250,000 B/D)	30 (75)	15-23 (50-75)	14-20 (46-66)	13-19 (42-61)	12-18 (40-58)	1	457 (1500)	1220 (4000)	Required space in turning basin can be reduced substantially should tug-assisted docking and departures be required
Large (500,000 B/D)	138 (340)					2-3	914-1371 (3000-4500)	1220 (4000)	
Very Large (<1,000,000 B/D)	300 (740)					3-4	1371-1829 (4500-6000)	1220 (4000)	
LNG Plant									In addition to thoroughput, size of plant will also depend on amount of reconditioning required for gas
(400 MMCFD)	24 (60)	13-16 (43-54)	11-14 (37-46)	10-13 (34-42)	10-12 (33-40)	1	304-610 (1000-2000)	1220 (4000)	
(1,000 MMCFD)	80 (200)	13-16 (43-54)	11-14 (37-46)	10-13 (34-42)	10-12 (33-40)	2			
Construction Support Base	16-30 (40-75)	9.1 (30)	6 (20)	6 (20)	5.5 (18)	5-10	304-610 (1000-2000)	304-457 (1000-1500)	Requires additional 61 m of dock space for each pipelaying activity being conducted simultaneously and each additional 4 platform installation per year

Source: Dames & Moore 1980c.

B/D = barrels per day

MMCFD = million cubic feet per day

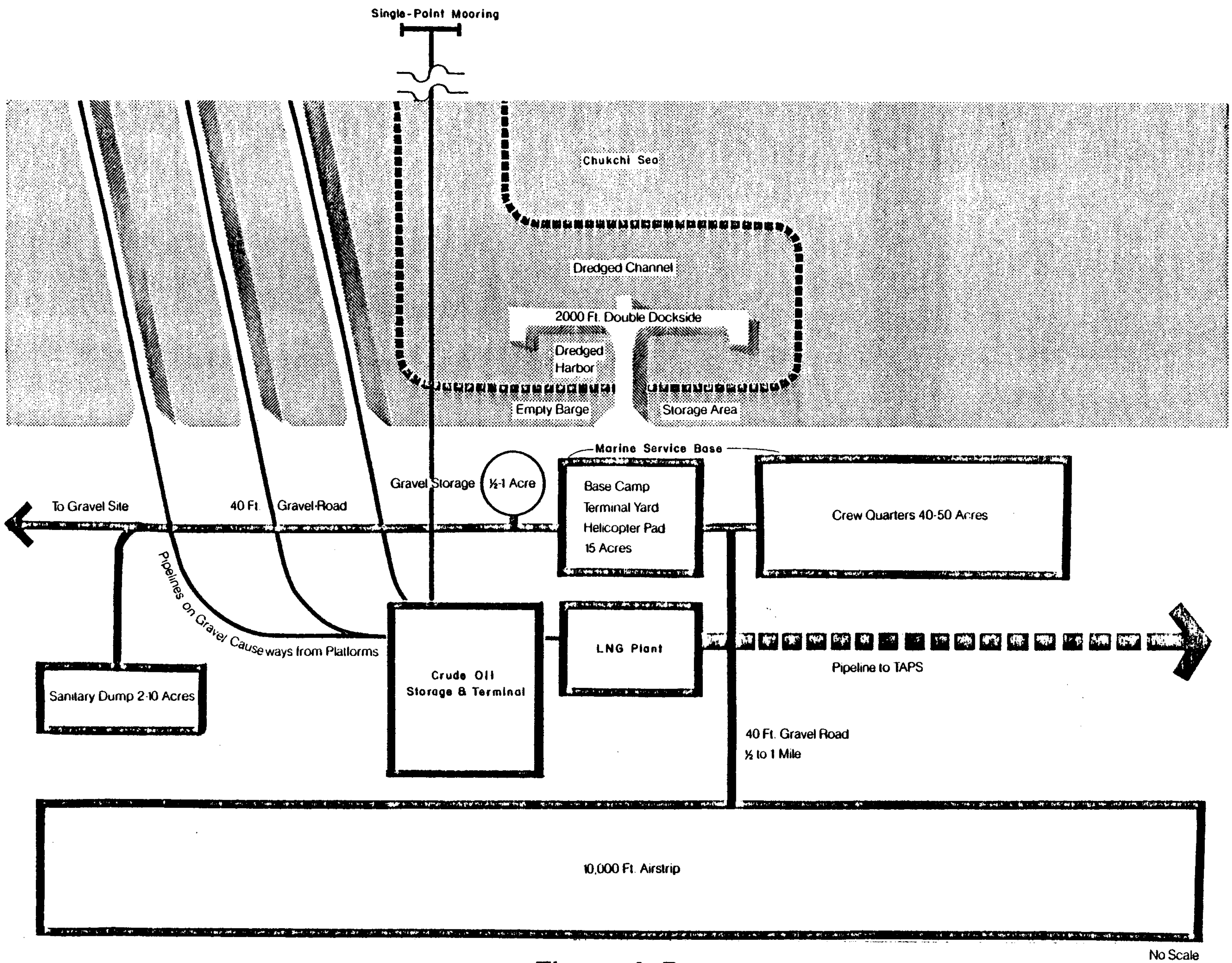


Figure 4-5
REPRESENTATIVE OIL & GAS DEVELOPMENT ONSHORE FACILITIES

- o Gravel deposits
- o Sediment dynamics (littoral drift)
- o Freshwater supplies

While the principal oceanographic, geologic and geomorphic characterization of the Barrow Arch planning area's coastlines have been discussed, both earlier in this chapter and in Chapter 3.0, more detailed studies of possible sites for onshore facilities will have to be conducted once a lease sale has been held. Nevertheless, the technical and environmental criteria for such a composite site ranking can be identified. They include:

- o Flat terrain and sufficient acreage
- o Proximity to known faults
- o Shelf width/water depth
- o Absence of navigation hazards
- o Sufficient elevation to avoid flooding and ice override events
- o Slope stability
- o Site physiography
- o Surficial deposits
- o Wave exposure
- o Ice conditions
- o Berth orientation to prevailing winds and current
- o Current speeds
- o Nearshore processes
- o Proximity to existing harbor and airport facilities
- o Proximity to marine mammal concentrations

4.5 Socioeconomic Setting and Regulatory Constraints

Coastal communities in the Barrow Arch planning area, notably Wainwright and Barrow, as well as a number of smaller native villages, are likely to be affected by oil and gas development. Coastal Zone Management regulations require advanced area planning to accommodate any sizable onshore energy-related installations relative to the communities affected by oil and gas development. This required planning addresses housing of personnel, appropriate land on which to site facilities, and existing services and utilities that may be impacted. To the extent desirable, the energy facilities can be made to be self-sufficient.

The administration of lands in the Barrow Arch planning area is split among several major holders. The North Slope Borough is responsible for taxation, development, and land infrastructure planning. The federal government also controls much of the land in the area as part of the National Petroleum Reserve - Alaska (NPR-A), and the State has some land holdings and controls the seafloor out to a 3-mile (4.8-kilometer) line beyond the coast.

A coastal management program for the North Slope Borough, pursuant to the federal Coastal Zone Management Act (CZMA) and partially funded by the Coastal Energy Impact Program (CEIP), is currently in the process of being developed. A coastal inventory and assessment is currently being prepared. The North Slope Borough and its constituent local communities will undoubtedly play a large role in responding to and directing the siting of energy facilities along Alaska's northwest coast.

The predominantly native population of the area is involved in a transitional economy featuring aspects of both a cash, wage-based economy and a traditional, subsistence economy. Much of the wage employment that exists is seasonal and a significant portion of the cash that enters the area comes through State and federal transfer payments.

Subsistence fishing and hunting activities are a significant economic contributor to Inupiat Eskimo villages and natives from the regional communities of Wainwright and Barrow. Care will have to be taken in siting and constructing any oil and gas-related onshore and coastal facilities to avoid adverse impacts on these activities.

4.6 Representative Onshore Facility Sites in the Barrow Arch Planning Area

Several studies have been conducted during the last 5 years to examine the feasibility of siting and developing major oil and gas-related onshore facilities, particularly for ports and marine terminals. Engineering Computer Optecnomics (1977) conducted an assessment of 29 potential port sites in Alaska including Point Lay, Point Hope, Kivalina and Kotzebue. Global Marine (1978), in its preliminary feasibility study of a tanker transportation system serving the northwest coast of Alaska, examined the siting of an oil terminal and storage facility near Cape Thompson. Bechtel (1979) prepared a conceptual design of an arctic marine terminal for transferring crude oil to ice-breaking tankers. They studied siting such a facility in the vicinity of Wainwright at Point Belcher on the basis of serving potential oil fields in the Chukchi Sea, NPR-A, or other onshore fields in northwest Alaska. McMullen Associates (1980) conducted an analysis of a marine transportation system for NPR-A that evaluated potential marine terminals sited at either Wainwright or Cape Thompson.

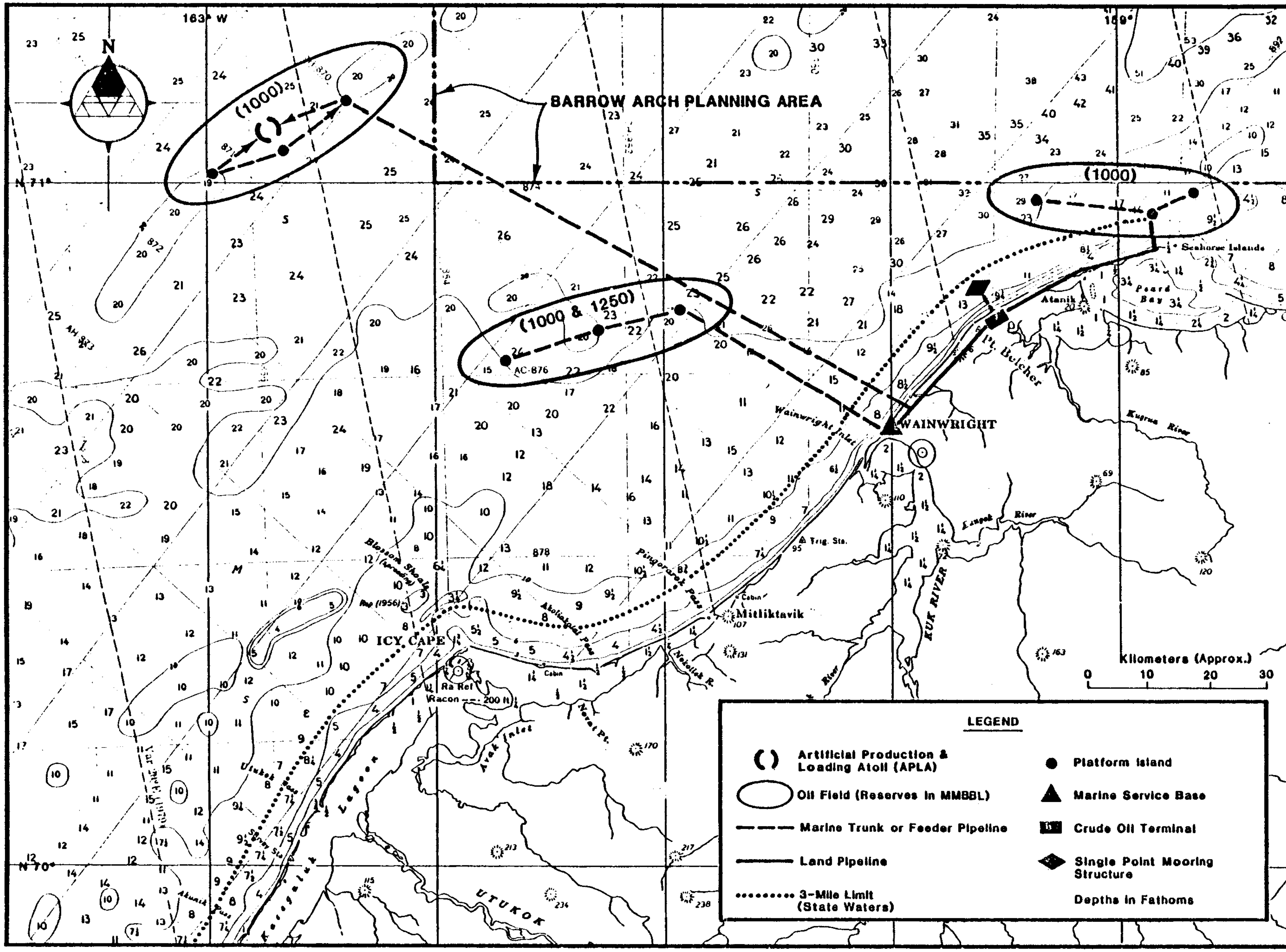
For the purposes of this study, two representative sets of offshore oil fields were established along with marine terminal sites to guide the economic analysis contained in Chapter 6.0. The most likely location of oil and gas reserves is in the northern part of the Barrow Arch lease area south of 71°N latitude. A terminal is likely to be located at Point Belcher near Wainwright due to the close approach of deep water to shore (relatively unusual in comparison to the rest of lease sale planning area). A pipeline to an SPM, 3 to 8 kilometers (1.4 to 4.4 nautical miles) in length, would be required to reach water depths sufficient to avoid tanker grounding, depending upon the size of the tankers selected to transport produced oil or gas (McMullen 1980).

Marine service base and harbor facilities are likely to be constructed in one of several places. To the northeast of Wainwright is Peard Bay. Just below Wainwright is Wainwright Inlet and the mouth of the Kuk River. Several passes into Kasegaluk Lagoon may be expanded and harbor facilities dredged out within the lagoon. Pingorarok Pass, north of the Nokotlek River, is one possible site. Further south, below Icy Cape, Icy Cape Pass or Utukok Pass enter Kasegaluk Lagoon near the Utukok River, which contains large gravel resources. In the vicinity of Point Lay, Kukpowruk Pass enters the lagoon between the Kokolik and Kukpowruk Rivers, both of which furnish gravel sources.

The second representative site of oil and gas fields is at the southern end of the proposed lease sale area. In the event of sizable finds of oil or gas, produced hydrocarbons might be moved south via marine and land pipelines to a marine terminal site near Cape Thompson, where deep water approaches close to shore and ice conditions are less severe. A site at either Kisimilok Creek or Ogotoruk Creek seems feasible. Depending on the actual terminal site and the size of the tankers used, pipeline lengths to a SPM in deep water would be between 5 and 10 kilometers (2.5 and 5.3 nautical miles; McMullen 1980).

Marine service base facilities are likely to be put in place at one of several locations for a southern field. Ayuyatak Lagoon, east of Cape Lisburne, might be dredged out and a pass through the barrier beach established. Noakok Pass into the southern-most end of Kasegaluk Lagoon might be expanded into harbor facilities or the passes in the vicinity of Point Lay might be utilized.

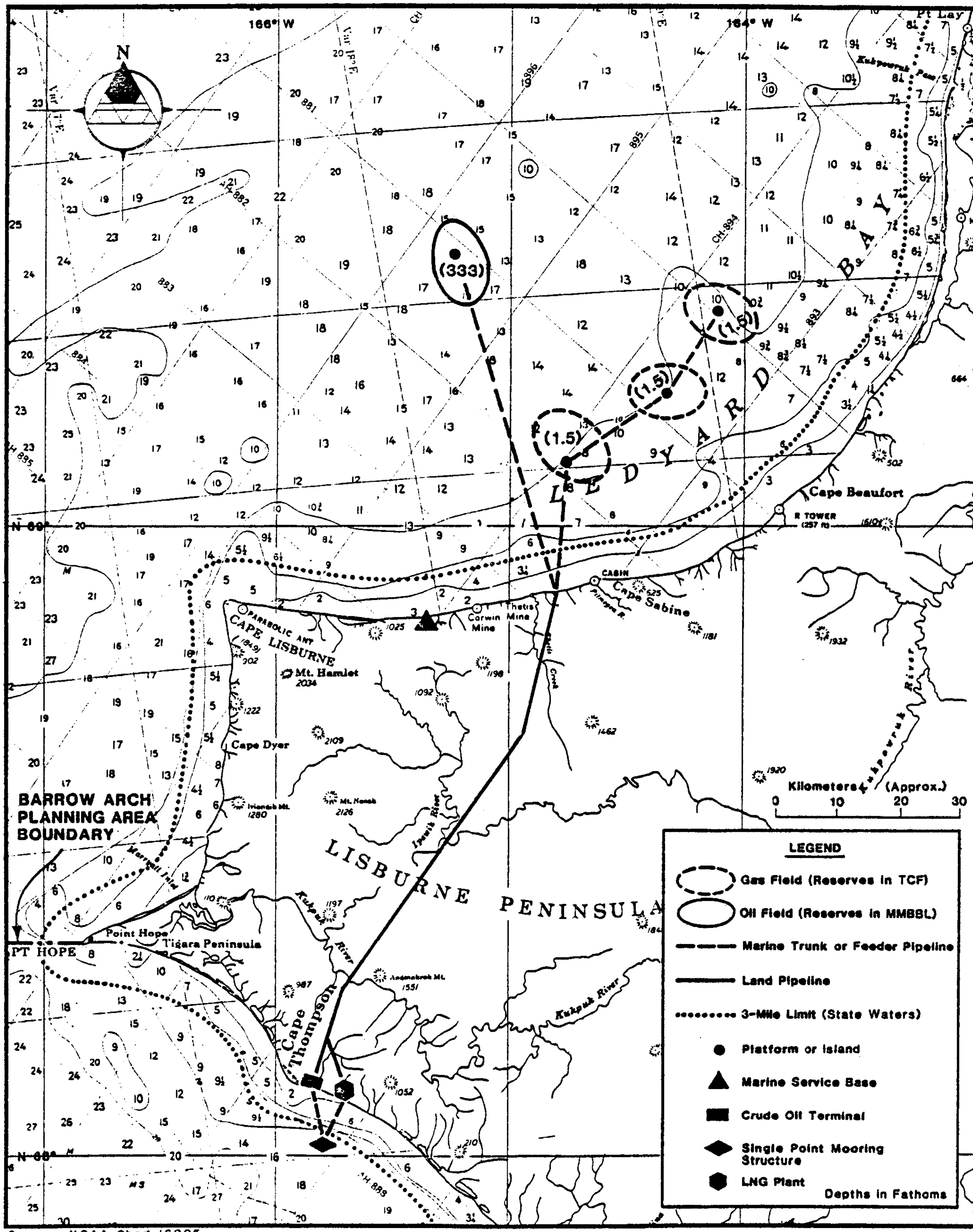
Figure 4-6 illustrates the location of representative offshore oil fields, platforms, offshore and onshore pipeline corridors, marine terminal sites, LNG plant sites, and marine support base sites in the northern part of the Barrow Arch planning area. Figure 4-7 illustrates the same type of facilities for fields in the southern portion of the lease sale area. (These are described in detail in Section 6.2.)



Source: NOAA Chart 16005, Cape Prince of Wales to Point Barrow

Figure 4-6

REPRESENTATIVE FIELD & SHORE FACILITY LOCATIONS - NORTHERN PORTION



Source: NOAA Chart 16005, Cape Prince of Wales to Point Barrow

Figure 4-7

REPRESENTATIVE FIELD & SHORE FACILITY LOCATIONS SOUTHERN PORTION