

State-of-the-Art Report on Offshore Concrete Structures for the Arctic

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The report brings together the relevant experience currently available in designing and building offshore arctic concrete structures. Design criteria have been highlighted, problem areas discussed and future research needs identified. The document is aimed principally at the arctic and sub-arctic areas bordering the United States and Canadian coastlines.

The arctic environment and its influence on structures are identified. Typical environmental and geotechnical conditions, types of ice features and efforts on ice surveillance and ice measurements are discussed.

*Existing and proposed forms of arctic structures are described. Design criteria, materials durability in the arctic environment and effects of coatings on reducing ice adhesion and friction are discussed together with special considerations **for** structural and foundation design.*

Construction methods, materials and special features of recently completed arctic structures have been described. Marine operations associated with the safe transport and installation of arctic concrete structures are addressed. Maintenance, inspection and repair techniques which may be used in relation to arctic structures are discussed. Finally, research and development needs to further improve the design of arctic concrete structures are identified.

Keywords: abrasion resistance; adhesion; admixtures; aggregates; arctic regions; bridge piers; caissons; chemical attack cold weather construction; **concrete construction**; concrete durability; corrosion; damage; earthquake resistant structures; failure mechanisms; **foundations**; freeze-thaw durability; friction; grouting; harbor structures; ice; icebergs; inserts; inspection; installing; limit state design; maintenance; marine atmospheres; moorings; offshore drilling; **offshore structures**; oil fields; permafrost; permeability; pore water pressure; prestressed concrete; prestressing steels; protective coatings; reinforced concrete; reinforcing steels; repairs; safety; settlement (structural); storage tanks; structural analysis; structural design; thermal stresses; towing; wind pressure.

ACI Committee Reports, Guides, Standard Practices, and Commentaries are intended for guidance in designing, planning, executing, or inspecting construction and in preparing specifications. Reference to these documents shall not be made in the Project Documents. If items found in these documents are desired to be part of the Project Documents, they should be phrased in mandatory language and incorporated into the Project Documents.

ACI 357.1R-91 replaces ACI 357.1R-85 effective May 1, 1991.

Numerous editorial and minor revisions have been made to the report. Year designations have been removed from standards and reports to make the current edition the recommended reference. Additional references have been added.

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1 .O-INTRODUCTION

This state-of-the-art report brings together relevant experience currently available in designing and building arctic concrete structures so that design criteria can be highlighted, problem areas discussed and future research needs identified, eventually leading to improved designs. It should not be treated either as a "Standard," "Recommended Practice," or "Guide." The report is aimed principally at the arctic and sub-arctic areas bordering the United States and Canadian coastlines (see Figure 1.1) but is also applicable to similar regions adjacent to Norway and the Soviet Union.

Concrete has long been proven a viable and cost-effective construction material for offshore structures in temperate and subarctic locations. Concrete lighthouses have been used in the St. Lawrence Waterway and in the Baltic Sea since the turn of this century (1.1). Concrete gravity platforms have been installed in the hostile waters of the North Sea since the early 1970s (1.2, 1.3). Considerable experience therefore exists in designing concrete structures for temperate and subarctic offshore conditions. Similar experience with structures within the Arctic Circle is, however, limited. The same is true for structures located in regions where encounters with icebergs are common such as the eastern seaboard of Canada.

To date, exploration in the offshore arctic has generally been in the shallow waters closer to shore and has taken place either from the ice itself, from artificial islands built of locally dredged material, from islands built of trucked material, and from spray ice islands. More recently, both Canadian and U.S. companies have built a few different forms of exploration structures for use in deeper waters. These have ranged from caisson retained islands and mobile gravity structures to floating vessels. Both concrete and steel construction have been used. Significant work has also been devoted to experimental testing and developing design criteria for composite construction (steel-concrete-steel). Several different concepts for mobile arctic concrete drilling structures have also been proposed and these are receiving serious attention.

A significant amount of engineering and research has been carried out in the Arctic by individual oil companies and by joint industry groups such as the Alaska Oil and Gas Association (AOGA), the Arctic Petroleum Operators Association (APOA) of Canada, and the Norwegian/German consortium sponsoring studies on Concrete Structures in the Marine Environment (COSMAR). Various concrete structure concepts and the use of new concreting materials are being studied in several joint industry and government sponsored projects. Most of this work usually remains proprietary for about five years, after which it becomes available for public use. However, most of these studies are immediately available on a cost sharing basis. An indication of future topics for research and development of concrete structures is included in Section 10 of this report. Engineering and research are also being carried out by government bodies, universities, and individual engineering companies results of which are reported in conferences such as:

- | | |
|--|--------|
| - International Association for Hydraulic Research | (IAHR) |
| - Port and Ocean Engineering under Arctic Conditions | (POAC) |
| - Behavior of Offshore Structures Symposium | (BOSS) |
| - Offshore Technology Conference | (OTC) |
| - Symposium on Offshore Mechanics and Arctic Engineering | (OMAE) |
| - Cold Regions Engineering Specialty Conferences | (ASCE) |

This report contains references and a bibliography on relevant publications.

The National Institute of Standards and Technology held a workshop where industry experts pooled their experience on arctic concrete structures and identified future research and development needs (1.4).

Several industry bodies are also active in furthering the understanding of arctic engineering. Apart from the American Concrete Institute (**ACI**), which has produced a guide ACI 357R*, the American Petroleum Institute (API) has published two guidance documents relating to arctic and offshore work. One is API RP 2A, the other is RP 2N. The Canadian Standards Association and the Federation Internationale de la Precontrainte (FIP) currently have working groups preparing documentation on arctic structures. FIP has recently completed and published an appendix on **Ice loading** considerations (1.7). In addition, there are several other international codes and guides such as the Canadian Standard CAN 3 S6 dealing with the influence of the arctic environment on structures in general (1.5-1.9). In particular, the Canadian Standards Association has published a preliminary code for the design, construction and installation of fixed offshore structures (1.9). This report supplements and cross references most of this previous work. Principal aspects affecting arctic concrete structures, e.g., environmental forces, foundations, marine operations, inspection, maintenance, and repair, are included to present the overall picture.

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* See Section 11.0 for Standards and Guides from ACI, API, etc.

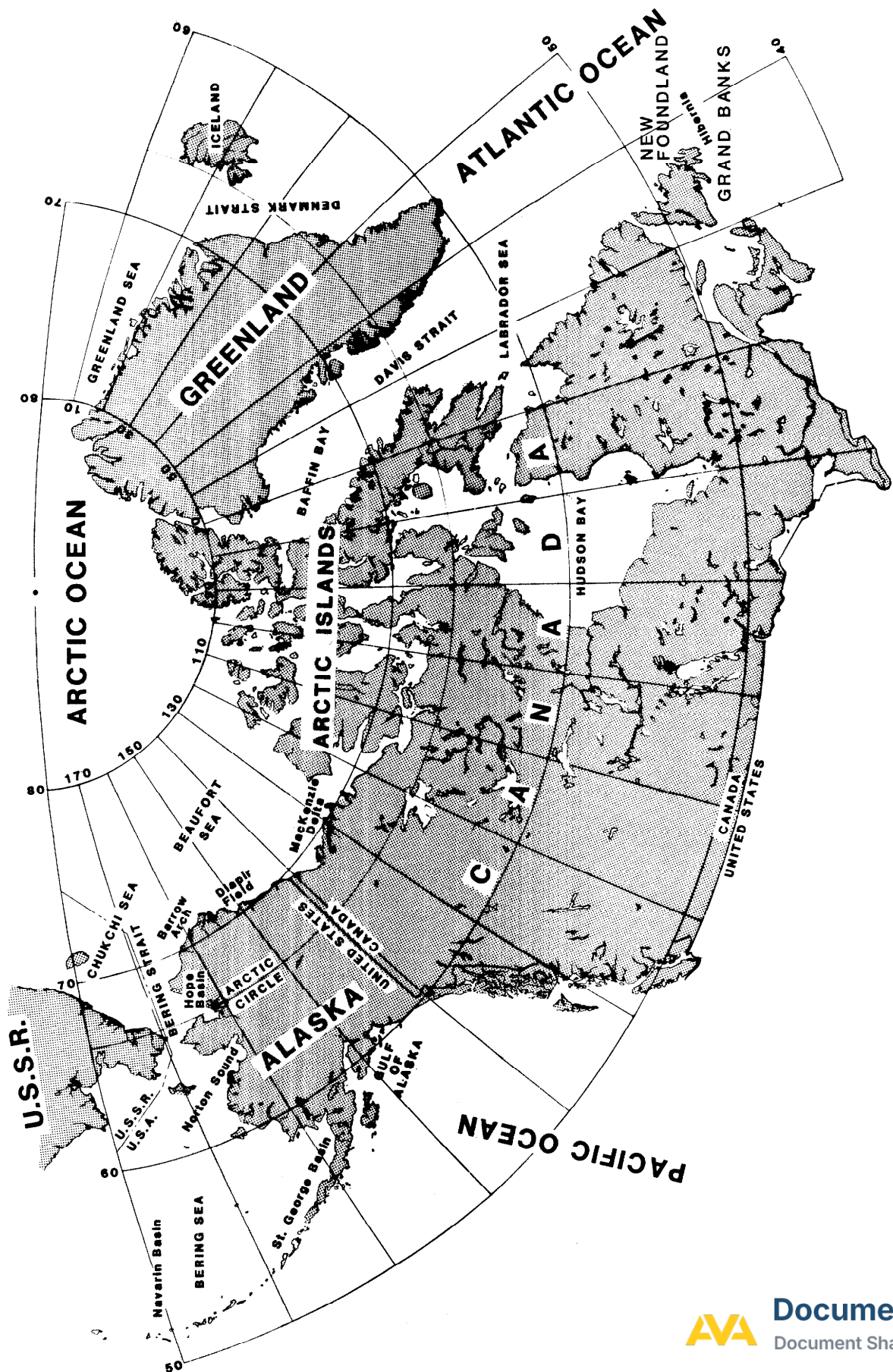


Fig. 1.1--Arctic areas around the United States and Canada

2.0-THE ARCTIC ENVIRONMENT AND ITS INFLUENCE ON STRUCTURES

The report is aimed principally at the arctic and sub-arctic areas bordering the United States and Canadian coastlines shown in Figure 1.1. For terminology relating to ice features, the reader is referred to RP 2N. Ice features which are of direct relevance to arctic concrete structures are described in Section 2.3.1.

2.1 -The U.S. Arctic

In discussing the physical environment of the United States offshore arctic regions, it is convenient to divide the area into two parts; the dividing line being in the vicinity of the Bering Strait. The area south of the Strait is classified as the Bering Sea environment and the area north of the Strait as the Beaufort/Chukchi Sea environment.

2.1.1 -Bering Sea

The Bering Sea environment is characterized in the winter months by a highly mobile (6-9 miles (10-15 km) per day) annual ice cover ranging from complete coverage just south of the Bering Strait to completely ice free just north of the Aleutian Islands. Although ice rafting is common, the parent ice sheet thickness varies from 3 to 5 ft (1 to 1 1/2 m) in the Norton Sound area and from about 1 1/2 to 3 ft (1/2 to 1 m) in the southern areas of St. George Basin. During the summer months, most of the offshore areas, except for areas near the Bering Strait, are ice free for at least five to seven months. The virtually unlimited south-westerly fetch can create severe storm activity generating waves approaching 50-100 ft (25-30 m) heights, in the deeper water areas.

2.1.2 – Beaufort and Chukchi Seas

The area from the Bering Strait to 70° N is very similar to the Bering Sea with an extended ice season. The rest of the Beaufort/Chukchi Sea environment is characterized by the presence of the polar ice pack most of the year. At sites along the coast, the ice generally retreats some distance offshore during the months of July, August and September when marine operations are possible then. The extent to which the Polar Ice Pack retreats offshore can, however, vary from year to year. In some years, there may not be an open water season at all. Multiyear ice and highly deformed first-year ice are formed in the coastal zone areas outside of the barrier island chain. By mid-winter, the landfast ice locked between the barrier islands and the coast, extends offshore to about 60 feet (18 m) of water depth. The landfast ice is relatively stationary further offshore. Ice drift velocities are on the order of 1 1/2 to 3 km per day, but much larger movements have occurred in association with winter storms. Normal wave conditions are relatively mild because of the proximity to the arctic pack, but local east-west storms, with wind velocities up to 100 knots (52 m/sec), can generate large waves during the open water season and cause large movements of ice floes during the break-up season.

2.1.3 – Geotechnical Conditions in the U.S. Arctic

Much of the area in the Bering Sea and in the Beaufort/Chukchi Sea contain high percentages of silts and sands. In Norton Sound and in the Bering Sea, for example, the sediment is very high in silt content because of the discharge of the Yukon and other rivers. The southeastern portion of the Bering Sea north of the Aleutian Islands contains sediments primarily of sand and gravel. As this region is earthquake prone, sand and gravel foundations have to be investigated for potential liquefaction problems.

The Chukchi Sea shelf is characterized by a dominance of sand near the shoreline, changing to silts further offshore. The Beaufort Sea shelf typically contains mostly silts and clays. Surface deposits of sand and gravel are relatively rare. A primary consideration in the shallow water areas is relic permafrost and gas hydrates. The occurrence of relic permafrost is related to the distance from the shoreline and is generally found in water depths less than 50 ft (15 m). The top of the permafrost is generally depressed below the mudline to depths depending upon water depths, soil conditions and other ocean conditions. At shore and near-shore islands, the permafrost level could be higher.

Ice gouges are formed in the shallow water areas of the Beaufort and Chukchi Seas and south of the Bering Strait in the Norton Sound area by drifting ice ridge keels which contact the sea bottom. The intensity of ice gouging is known to be related inversely to water depth, but the highest intensity of gouges is observed in water depths from 65 to 100 ft (20 to 30 m). For foundation designs near river mouths, strudel scours should be investigated. Strudel scours are craters in the sea floor as much as 80 feet (25 m) wide and 20 feet (6 m) deep, that are excavated by vertical drainage flow during the yearly spring flooding by fresh water runoff of vast reaches of shorefast sea ice surrounding arctic deltas.

Chapter 6.0 provides additional information on conditions in the arctic region.

2.1.4-Other Conditions In the U.S. Arctic

Tidal variations are generally small around the coastlines. Storm surges can, however, be an important design parameter, particularly in “closed” areas such as Norton Sound where surges in excess of 15 ft (4.5 m) have been recorded. Other environmental hazards that can exist are current induced scour, gas charged bottom sediments, peat intrusions, and geologic faults. Air temperatures can reach -50°C in most areas of interest.

The seismicity is highly variable. The most seismically active areas are those near the boundary between the Pacific and the North American plates such as Bristol Bay, St. George Basin, and the Navarin Basin. Areas north of the plate boundary such as Norton Sound, the Chukchi, and Beaufort are relatively inactive.

For structures located in Norton Sound and northward, it is unlikely that seismic forces will significantly affect their design. However, structures located on the fringe of the Aleutian seismic zone, such as in the southeastern area of St. George Basin, may be influenced by seismic considerations.

2.1.5 – Information Sources

Useful information on the arctic environment in particular areas can be found in the Environmental Impact Statements prepared by the U. S. Department of the Interior (2.1, 2.2, 2.3, 2.4, 2.38) and similar documents prepared by other agencies (2.5). A useful summary of ice conditions encountered in various arctic areas is given in Reference 2.6. References describing the arctic environment can also be found in API RP 2N. References 2.7 and 2.8 also provide useful information.

2.2 -The Canadian Arctic

The Canadian offshore arctic areas are generally classified into the Beaufort Sea, Mackenzie Delta, the High Arctic, and the East Coast. These areas differ principally in the type and content of ice (2.9).

2.2.1 -Canadian Beaufort Sea/Mackenzie Delta

This area is generally ice covered from about mid-October through mid-July. The nearshore area, out to about the 65 ft (20 m) water depth, becomes landfast by mid-winter, and remains relatively stationary until break-up. This allows for winter drilling from artificial islands and re-supply over thickened winter ice roads, as well as for winter island building programs. The band of broken ice which separates the landfast ice from the mobile polar pack is known as the shear zone. In common with the U.S. sector, the shear zone contains a high proportion of consolidated pressure ridges. In general, the motion of the pack is from east to west, as a part of the Beaufort Gyre. There is evidence of a reversal of the Beaufort Gyre occurring in August, however. The mean daily velocity of the pack ice varies throughout the year from a mid-winter minimum of about 1.5 miles (2.5 km) per day to a maximum in mid-summer in excess of 6 miles (10 km) per day. The mean annual concentration of multiyear ice varies from less than 10 percent near the shore to almost continuous multiyear ice in the polar pack. Design features to consider are multiyear floes, ridges and hummock fields, as well as ice islands and their fragments. Waves during the summer months must be considered in the design. The position of the pack relative to the shore, and the wind direction and strength, are important factors in determining design wave heights. Further information can

Environmental Impact Statement (2.10) and Reference 2.11.

2.2.2 -The High Arctic

The High Arctic, or the area around the Arctic Islands (See Figure 1.1), has seen a great deal of activity due to the considerable quantities of hydrocarbons, principally natural gas, discovered there. The temperatures are lower than in the southern Beaufort Sea. As a result many areas never become completely ice free in the summer, the ice is thicker than in the southern Beaufort Sea and relatively stationary in the winter. Artificially thickened ice platforms have been used successfully in this area for winter drilling in deep water where the ice movements are limited.

2.2.3 -The East Coast

The East Coast area comprises the Davis Strait, the Labrador Sea, and the Grand Banks. The presence of glacial ice in the form of icebergs, bergy bits, and growlers are common to these areas. These features govern the design, at least for local loads due to the higher ice strengths of glacial ice, for both bottom founded and floating production concepts. Sea ice of up to 6 ft (2 m) thickness, and rafted ice, are design considerations, especially for floating production systems. Designs must also account for large waves generated over the virtually unlimited fetch of the Atlantic, with the worst time for waves being the winter months of January through March. Exceptions are areas that are covered with large amounts of ice, such as the Davis Strait and Labrador Sea, as the ice inhibits the development of large waves. The greatest influx of glacial ice is during late spring to early summer. Wave, current and wind driven ice is a design factor, due to the high velocities that may be attained.

2.2.4 – Geotechnical Conditions in the Canadian Arctic

The seabed soils of the Canadian Beaufort Sea are dominated by sedimentation from the Mackenzie River. Coarse grained sediments can be found in the western part of the Beaufort Shelf as well as in the extreme east. The Mackenzie Bay and the adjacent areas contain mostly soft, recent silt deposits.

The seafloor conditions in the Canadian High Arctic are expected to be highly variable. In the nearshore areas, the seafloor could include variable thicknesses of coarse-grained sediments such as sand and gravel or soft clayey or silty soils overlying rock.

The Canadian East Coast seafloor generally contains thick sand deposits, but can also include remnants of moraines and buried valleys filled with soft silt. Relatively thin clay layers can also be found interbedded in the sand deposits.

Further information on soil properties in the Canadian Arctic can be found in References 2.7 to 2.9.

2.3-Environmental Effects on Offshore Arctic Structures

The decision to select a particular form of structure for a given location will depend on a number of interrelated engineering and economic considerations. Nevertheless, environmental conditions will play an important part in establishing structural configurations. This section highlights the various effects of the environment that need consideration in the design of arctic structures. Further detailed discussion is given in Reference 2.12.

2.3.1 -Ice

2.3.1.1 -First-Year and Multiyear Ice

Ice forms and disperses annually in the lower reaches of the Arctic. This first-year ice is usually much weaker than the multiyear ice which grows year after year in the higher latitudes. Depending on its strength and thickness, the ice can be induced to fail by either crushing against the structure or by riding up its surface to fail in flexure. The crushing loads will depend mainly on the width of the structure, strength of ice, and its strain-rate. The flexural loads will be governed by the shape and slope of the structure and the thickness

and strength of the ice. Methods for calculating these loads are given in API RP 2N. Continuous crushing of sheet ice against small cylinders could create dynamic and fatigue problems. These have been addressed in Reference 2.13. A literature review on ice loading is contained in Reference 2.14.

2.3.1.2-Ridges

Ridges are the result of ice sheets deforming and fracturing due to the pressure caused in the ice field. The fractured ice pieces reconsolidate. The strength and consolidation of the ridge will depend mainly on its temperature and age. Keel depths of floating ridges can equal the water depth but ridges can also become grounded and gouge deep into the seabed. Size and frequency of ridges at a particular location could influence structural configurations. Ridges with small cross sections can be induced to fail in horizontal flexure against a vertical-sided structure. Multiyear ridges with large cross-sectional areas may require structures with sloping faces which enable the ridge to ride up or down depending on an upward or downward sloping cone and fail in vertical flexure before scattering around the structure. The length of the ridges and their extent of embedment in a floe or sheet ice are important in determining the forces caused. The frictional coefficient between the ice and the structure is also important in determining the resolution of forces. Ridge loads have been predicted by using plastic limit analysis reported in Reference 2.15 and by methods using the beam-on-elastic-foundation approach.

2.3.1.3 – Floes and Icebergs

Floes and icebergs are sections of ice which have separated from larger formations and that drift with the wind and current. Floes can be either of sheet ice or rafted sheets, reaching thicknesses up to 25 ft (8 m) and lateral extents of several kilometers. Icebergs of up to 50×10^6 ton mass and 420 ft (130 m) keel depth have already been considered in conceptual designs of offshore structures. Bergy bits and growlers are smaller pieces of iceberg ice. Bergy bits generally extend 3 to 16 ft (1 to 5 m) above the surface of the sea and have a horizontal area at the water-plane of 1100 to 3200 ft² (100 to 300 m²). Growlers extend less than 3 ft (1 m) above the surface of the sea and have a horizontal area at the water-plane of less than 220 ft² (20 m²). The major structural influence these ice features is due to impact. The effects include high local stresses at the point of impact, transfer of high impact loads to other parts of the structure and resistance of the foundation system to the total ice load (global forces). The compliance of the soil/structure system will play an important part in determining the loads imparted by an impacting floe or iceberg. With extremely large rare event ice features the risks associated with the structure displacing with respect to its foundation will need to be examined. Methods for designing for floe impact are described in References 2.16 and 2.17.

2.3.1.4 – Natural Ice Islands

Other ice forms, such as ice islands, which are the same as icebergs (fresh water glacial shelf-ice) occur in some areas of the Beaufort and Chukchi Seas. Although their occurrence is rare, the thickness could reach 350 ft (105 m) or more and the loads imposed by such features could be much greater than the loads due to multiyear sea ice.

2.3.1 S-Rubble Fields

Rubble fields are formed when ridges and other ice features ground on the seafloor and ice fragments pile up on top. They can also be formed when moving ice encounters an obstacle e.g., an offshore structure. Quite often rubble fields act as a cushion between a structure and other larger ice features, e.g., fast moving floes which may otherwise cause a hazard to a structure. Their major disadvantage, however, is that when access to a structure is from the ice, the rubble field poses a formidable barrier around the structure. A method for determining the forces imparted to a structure by other ice features acting through rubble fields, using the limiting driving force concept, is given in Reference 2.18. The mechanics of rubble field formation and its effect on the sliding resistance is also addressed in Reference 2.19.

2.3.1.6 -Adfreeze

Ice features can bond to structures if they remain stationary and in contact for extended periods. Ice can bond strongly to concrete surfaces and consequently can prevent desirable failure modes from taking place. This is particularly relevant where structures with sloping surfaces are designed for lower loads from ice features riding up and failing in flexure. A method for computing adfreeze forces is given in Reference 2.20 and API RP 2N. Adfreeze forces can be substantially reduced if low bond coatings are used on the surface. Further information on such coatings is given in Section 5.11.

2.3.1.7 – Local Contact Pressures

The composition, strength and strain-rate in an ice feature determine the contact stress imparted to a structural member. The design contact stresses will also depend on the structural framing considered since, in general, smaller tributary areas of structures will be designed for higher stresses. Care is necessary in selecting realistic contact stress relationships as this will dictate member thickness and may determine whether a structure can be floated out within the draft restrictions. The subject has been considered for a number of years and several opinions have been expressed on the magnitude of the contact stresses. These are summarized in References 2.21 and 2.22. Probabilistic methods for determining ice contact pressure have been proposed in References 2.16 and 2.17. API PN 2N provides ice pressure curves for both multiyear and first year ice. Depending on contact area, these pressures vary widely with minimum values of less than 200 psi (1 MPa) to maximum values of 4000 psi (28 MPa). A recent publication (2.37) on ice mechanics provides further insight to the ice contact pressure development. The design basis will become better quantified as further structures are installed and more measurements are obtained.

2.3.1.8-Dynamic Effects of Sea Ice

The dynamic character of ice forces is caused by the periodic ice pressure growth, followed by decay due to fracture observed both on small diameter vertical cylinders (or indenters) and also on sloping surfaces. Wave motion and the presence of ice also generate periodic impact on a structure. In addition, the vibration of the structure itself will influence the ice loads and the dynamic ice-structure interaction should be examined. In areas where structures are designed for seismic forces, the effect of sea ice around the structure, together with its added mass effects, should be considered. In 1988, the Molikpaq, a mobile caisson reinforced island (CRI) constructed from steel, and with its hollow interior filled with dredged material, underwent significant vibrations when a large, multiyear ice floe pushed past it. The internal fill material upon which a working platform sat, liquified and consolidated as much as 5 ft. (1.5 m) in some locations. The exact events and consequences are still being studied.

2.3.2 -Waves

Waves can also cause a significant effect on arctic structures. In some areas of the Arctic, and in most areas of the sub-Arctic (Bering Sea, Eastern Canada, etc.), the global wave forces may exceed the global ice force and thus control the foundation stability. Ice, however, will usually control local loads.

Large displacement gravity structures will attract substantial loads which can be computed using the linear diffraction theory developed for structures in the North Sea (2.23). Care will, however, be needed in establishing wave forces in shallow water where the waves become nonlinear. The effect of large underwater shapes like cones, berms, etc., can cause the wave regime to be altered in the vicinity of the structure. This in turn can lead to substantial alteration in overall wave forces and also in the phase differences between the force components.

Another important parameter in dealing with waves is the determination of the freeboard. Wave splash, spray and run-up can be considerable in large volume structures in shallow water.

2.3.3 – Earthquakes and Seaquakes

Although ice loads often represent the dominant form of loading for arctic offshore structures, other types of loading must be considered in design. As many areas of the Arctic are subject to intense seismic activity, arctic offshore structures must be capable of resisting forces generated by earthquakes and seaquakes. The methods applied to check the earthquake survivability of onshore structures are generally applicable to offshore structures as well. In using these procedures, however, due account should be taken of some important differences (6.21):

- Offshore structures are often large, and thus more likely to be affected by out-of-phase motions.
- Offshore structures often have considerable added mass and damping from the surrounding water and ice, and as a result the long-period components of ground motions are more important than for onshore structures. When surrounded by ice, the interaction may develop high local forces which should be considered.

The design of offshore concrete structures to resist earthquakes in the Gulf of Alaska has been described in Reference 6.22. Ensuring nonlinear, ductile behavior of concrete components is of particular importance as explained in Section 4.6.2.

Seaquakes have not been widely reported or discussed, and their mechanisms are incompletely understood. They result from the transmission of earthquake generated p-waves through water, and have caused severe damage to ships in a number of well-documented cases (6.23). Seaquakes have a potential for causing severe damage to ships and possibly fixed platforms in both deep and shallow water.

2.3.4 – Effects of Other Environmental Conditions

Among the other environmental conditions which have a significant effect on arctic structures is the geotechnics of the sea bed, including the presence of permafrost. These conditions will determine the shape and size of the structure and the means for achieving adequate foundation resistance whether it be by gravity forces, piles, or methods for improving the soil strength by consolidation. The location of permafrost and soil conditions will dictate foundation failure modes and magnitudes of settlement.

Another seabed condition of importance is the presence of ice gouges which occur in most arctic areas. These will influence the extent of support afforded by the seabed and also dictate the design of the structure's interface with the seabed. Section 6.0 further discusses geotechnical considerations affecting arctic concrete structures.

Low air temperatures in most arctic areas cause severe thermal gradients through the concrete and influence the structural design, particularly at the air-water interface. The cycling of temperature through the freezing point needs special consideration from the material selection standpoint. This is especially important in the splash zone where the concrete may be saturated and where wave action and storm surge may thaw the frozen concrete causing continuous freezing and thawing cycles.

Tides and surges can be classed as secondary conditions which affect the structure. They alter the sea levels and consequently the wave loads. They also determine the point of application of ice loads. Wind and current fall into the same category. Winds will be important in the design of the superstructure and in determining the extent of superstructure icing (2.24). Waves and currents determine whether seabed scouring is a potential problem (2.25).

2.4- Efforts on Ice Surveillance and Measurements in the Arctic

For arctic structures located beyond the landfast ice zone or in iceberg areas, surveillance of approaching ice formations may be needed both for safety considerations and to correlate actual conditions with design

assumed in design. Considerable effort has been spent in recent years to monitor ice cover and ice movement on the macroscale by satellite remote sensing (2.26), (2.27) and on the mesoscale by air and vessel borne radar systems and forecasting models (2.28 to 2.32).

Much effort has also been directed toward direct measurement of ice forces on various structures in moving ice fields. Reference 2.33 provides a partial, historical review of ice load measurements programs on piers and piling describing the various tests and instrumentation employed. Instrumentation for ice load measurement was deployed on the Tarsiut concrete caisson structure (2.34). Other work (2.35 to 2.37) reports on instrumentation types and new developments. Such work will be useful in developing and specifying environmental monitoring and instrumentation systems during the design of future structures.

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3.0-ARCTIC CONCRETE STRUCTURES

3.1 -Existing Structures

3.1.1 -Bridge Piers and Harbors

Concrete structures have been built for many years in locations exposed to severe ice attack. One of the first applications was in construction of bridge piers in rivers subject to annual ice break-up. Numerous examples of these structures now exist in northern latitudes of North America, Europe, and Asia (3.1). Harbors located within the Arctic Circle have also utilized concrete piers and breakwaters (3.2 to 3.4).

3.1.2 -Scandinavian Lighthouses

Many concrete lighthouses have been built in the Baltic Sea in the last 40 years (Figure 3.1). Most of these structures were floated-in and ballasted to the seafloor, a technique widely used more recently in the North Sea. Some Scandinavian lighthouses were constructed above water on piles and then “launched” by collapsing the piles with explosive charges. Reviews of the various lighthouses built in Scandinavia can be found in References 3.5, 3.6, and 3.7.

3.1.3-Canadian Lighthouses

Some 70 lighthouses, mostly of concrete construction, have been built in the St. Lawrence Waterway since 1902, the majority since the early 1950’s (3.2). Many of these structures are familiar to designers of offshore arctic platforms as they exhibit cylindrical, conical and hour-glass configurations (Figure 3.2) to cope with high river currents and ice floe impact.

3.1.4-Oil Field Related Structures

3.1.4.1 -Early Cook Inlet Platforms

Oil field development in the upper Cook Inlet dates back to the early 1960’s. A total of 14 offshore platforms were installed between 1964 and 1968 (3.8, 3.9). These platforms were of steel construction and were designed for fast moving first-year ice floes. A considerable amount of research and development was carried out prior to installation of the platforms. These platforms have successfully withstood the arctic environment for nearly twenty five years.

3.1.4.2 – Beaufort Sea Platforms

Structures are being designed and installed in the more severe environment of the Beaufort Sea, again following substantial research and development.

A variety of construction materials are being used depending upon the environmental conditions, ease of construction and market conditions. Ice islands and gravel islands initially proved to be the most cost-effective exploration structures in the shallow waters of the Beaufort Sea. Details of these early structures are discussed in References 3.9 and 3.10. Dome Petroleum and Gulf Canada have pioneered the use of three different designs of mobile exploration units in deeper water. A bottom founded truncated tanker hull, strengthened by concrete infilling, was developed by Dome Petroleum in the Canadian Arctic in September 1982 (3.11). Gulf Canada has commissioned the Mobile Arctic Caisson which uses a steel annular unit

positioned on a gravel berm and retained in position by gravel infill (3.12). Gulf Canada has also commissioned the Kulluk, a steel conical floating drilling unit, was used in light ice conditions in the Canadian Arctic (3.13). Arctic drillships have also been used for exploratory drilling in these areas.

Another mobile drilling system, the Molikpaq (also called the MAC, for mobile arctic caisson), has also been deployed in the Canadian Beaufort Sea. The Molikpaq is essentially a mobile caisson reinforced island constructed from steel. At the drill site, the steel caissons are initially ballasted to the seafloor or to a subsea support berm. The resistance to sea ice is further enhanced by filling the hollow interior of the caisson with dredged fill material. Its* first application took place during 1984-85 at the Tarsuit P-45 site in 84 feet of water. A 16.5 foot subsea berm was used to set down the Molikpaq.

So far, concrete structures serving oilfield operations have been installed in two locations in the Beaufort Sea and two locations in the Baltic Sea.

3.1.4.3 – Sohio's Shore Protection Structures in Concrete

In 1980 and 1981, Sohio Petroleum Company (3.14) installed a precast concrete pier, a precast concrete seawall, and a slope protection system consisting of articulated, linked concrete mats, at the barrier islands in the Alaskan Beaufort Sea (Figures 3.3 and 3.4). The unitized concept for these three structures was intended to provide for rapid deployment, portability and reusability. The slope protection system is now permanently installed on Endicott islands and causeway.

3.1.4.4 – Dome's Tarsiut Island

The first arctic offshore concrete structure in the Canadian Beaufort Sea was built and installed by Dome Petroleum in 1981 (Figure 3.5) and subsequently operated by Gulf Canada. The Tarsiut Caisson Retained Island (CRI) (3.15, 3.16, 3.17) was located some 25 miles from land in the shear zone between winter land-fast ice and the constantly moving Arctic Gyre. After 2 years of successful performance, the concrete caisson was dismantled, refloated and transported to a storage area for possible future use.

Four large prestressed concrete caissons 226 ft x 50 ft x 35 ft high (69 m x 15 m x 11 m high), constructed of semi-lightweight concrete, were built in Vancouver, B.C. and towed around Alaska on a submersible barge. They were founded on a berm of dredged sand which extended from seabed at -70 ft (-21 m) to -20 ft (-6 m) below the waterline. The space between the four caissons was then filled with dredged sand to form the working floor for the drilling rig and associated facilities. Design information and construction details are described in Reference 3.17. Reference 3.18 describes general details regarding the monitoring of the island performance.

3.1.4.5 – Exxon's Concrete Island Drilling System

A concrete island drilling system (Figure 3.6), named the Glomar Beaufort Sea I (and often referred to as the CIDS or Super CIDS), was built in Japan by the Global Marine Drilling and was initially used in the Alaskan Beaufort Sea in August 1984. The unit comprises a steel mud base, approximately 295 ft x 315 ft (90 m x 96 m), a cellular concrete mid-section, 233 ft (71 m) square and a steel deck consisting of two separate, barge-like sections. All components of the Glomar Beaufort Sea I were built separately and assembled in sheltered waters in Japan before being towed to location. The operating depth of the mobile unit is between 35 and 55 ft (12 and 17 m).

The structure was designed for global ice loads of 460 kips per foot of width (6.7 MN/m), during the winter or 130,000 kips (580 MN) total floe impact loads during the summer. Local design ice pressures are about 900 psi (6.2 MPa) on a 5 ft (1.5 m) square patch of ice wall. In an effort to safeguard the structure against ice features larger than the design event, the Super CIDS can be surrounded by a grounded artificial ice barrier formed by water sprayed from the platform. Further design information can be found in Reference 3.19.

3.1.4.6-Texaco's Concrete Gravity Structures for the Baltic Sea

Deutsche Texaco has built two concrete production platforms for its Schwedeneck in the Baltic Sea (3.20). The platforms operate in 50 ft and 82 ft (15 and 25 m) of water. Each platform comprises a cellular concrete base with nine cells, the central cell being extended above the water level to support the deck (Figure 3.7). The overall base dimension is 125 ft (38 m) and the cells are approximately 40 ft (12 m) in diameter. Six foot skirts are provided under the base to achieve sliding resistance against ice forces which can be about 1,600 kips (7.2 MN). The cells are filled with sand to increase the effective weight. The platforms were installed in November 1983 and went into full operation in mid-1985.

3.2 -Proposed Arctic Concrete Structures

Many research, design and development studies have been carried out on different concepts.

Some of these concepts have been described historically in Reference 3.9 which also suggests possible future development trends in different arctic areas. Reference 3.8 describes 51 concepts currently proposed for arctic use. Some of these concepts which utilize concrete construction are described below.

The proposed concepts can broadly be separated into “Monopods/Monocones” and “Caissons.”

3.2.1- Monopods and Monocones

3.2.1.1- Monopod Drilling Rig

This structure (Figure 3.8) was intended for use in water from 10 to 40 ft (3 to 12 m) deep in Mackenzie Bay (3.21). The Monopod is essentially a steel structure, but incorporates a 5 ft (1.5 m) thick peripheral concrete ring around the hull which lends it stability and protection from impact. The enclosure on top of the hull can be filled with locally dredged soil ballast for additional weight if required. The monopod was, however, never built although “Approval in Principle” was obtained from the Canadian Government. The reason offered was that man-made islands were technically and economically more attractive for exploration drilling in shallow arctic waters.

3.2.1.2 – Fixed Monocone Drilling Rig

As the water depth increases, the construction of gravel islands becomes increasingly difficult and costly, and other types of drilling platforms become more attractive. Oil companies are conducting research and development work on alternative drilling methods that would be applicable in deeper arctic waters. Prominent among these are mobile concrete gravity structures which are designed to break the ice in bending rather than crushing, at significantly reduced loads. Both concrete and steel structures have been proposed.

Esso Resources Canada developed a preliminary design for a conical structure (Figure 3.9) for use in Mackenzie Bay in a water depth range of 65 ft to 130 ft (20 m to 40 m) (3.22). The structure consists of a large-diameter circular hull, a 450 degree cone section with 40 ft (12 m) diameter at the top, and a multistory deck section. The hull is designed for impact by deep-keeled ice features and serves two main functions: (1) to provide resistance against sliding and overturning when the structure rests on bottom; and (2) 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. A smaller cone structure for 30 to 65 ft (10-20 m) water depth, with a hull diameter of 330 ft (100 m), was also designed.

3.2.1.3-Adjustable Monocone Drilling Rig

The gravity structures described above are intended for exploration drilling. Their depth range capability is limited by the requirement that the cone must be in a certain position relative to the water level, to minimize ice loads. This is a severe constraint for an exploration concept, limiting its applicability to a narrow depth range in the particular ice environment for which it is designed.

Esso Resources Canada also developed an adjustable monocone concept (Figure 3.10) to reduce the limitations of water depth placed on structures with a fixed zone of ice-breaking capability. The concept uses a moveable conical collar that can be adjusted vertically on a cylindrical shaft to the optimum position for ice breaking (3.22). Advantages over structures with a fixed cone designed for the same depth range are (1) reduced weight; and (2) reduced cone surface area where heating or special coatings may be required to prevent ice from freezing to the structure. Adjustable monocone designs have been developed for three water depth ranges: 30 to 75 ft (10 to 24 m), 65 ft to 130 ft (20 to 40 m), and 130 ft to 200 ft (40 to 60 m).

3.2.1.4-ACES

Monocone designs described above are designed to resist multiyear pressure ridges up to 45 ft (14 m) thick. This design criterion was judged to be adequate for applications in the Mackenzie Bay area, where the frequency of multiyear ice invasions with heavy consolidated pressure ridges is relatively low. However, this criterion may not be sufficient for the Alaskan Beaufort, where grounding multiyear ridges occur in water depths beyond 18 m. In order to reduce potential ice loads developed from interactions with such large multiyear pressure ridges, cone angles of less than 45° need consideration. The Arctic Cone Exploration Structure (ACES), developed by Chevron, Exxon, and Shell (3.23) is intended for use in these conditions (Figure 3.11). The structure has a base diameter of 550 ft (168 m) and is designed in lightweight post-tensioned concrete. It features a multiangle cone and is intended to function as a mobile unit in a water depth range of 50 to 110 ft (15 to 35 m). Different versions for shallower and deeper waters have also been developed.

3.2.1.5-Detachable Monocone

In 1979, Dome Petroleum undertook a preliminary design of an Arctic Production Monocone. This concept (3.24) had a steel cone supported on either a steel or a concrete disc shaped base, 420 ft (128 m) in diameter (Figure 3.12). The cone was designed with releasing type fastenings to the base so that the site could be evacuated under rare ice events. During disconnect, the base would remain on the seafloor until the ice feature had passed. The cone would then be returned and reconnected to the base.

3.2.1.6 – Monocone Loading Terminal for Norton Sound

An Alaskan Oil and Gas Association (AOGA) joint industry study (3.25) involving fourteen oil companies, led by ARCO, investigated the feasibility and costs of a concrete monocone structure for storage and loading of crude oil in Norton Sound (Figure 3.13). The structure comprises a wide-necked monocone which houses oil related facilities. The structure is surmounted by a rotating turret carrying a loading boom and mooring equipment. Ice breaking tankers can moor up to the structure and operate on a year-round basis. The structure would be used on a stand alone basis initially, storing an adequate quantity of crude oil, but can be tied into shore based storage and processing facilities as the production expanded.

3.2.2 -Caissons

3.2.2.1 -Caisson on Extended Base

In 1979, Dome Petroleum studied an alternative concept which used a vertical sided caisson instead of the conventional cone shape. This structure was known both as Deep Caisson and Prestressed Concrete Caisson Platform (3.26). The caisson had a disc shaped base with a diameter of some 230 m (Figure 3.14). The caisson body consisted of a fluted cylinder with radial and circumferential internal bulkheads. It was designed for 60 m water depth and provided storage capacity for about 3.75 million barrels (0.5 million m³) of oil. This massive structure was estimated to contain some 490,000 cu yd (375,000 m³) of concrete.

3.2.2.2 -Caisson Retained Islands

Caisson Retained Islands (CRI) in both concrete and steel continue to be in the forefront of development concepts. Sohio Construction Company undertook a feasibility study for a concrete CRI in 1982 for possible use in the Alaskan Beaufort Sea (Figure 3.15).

Concrete caisson ringed islands also formed some of the production systems considered in the Environmental Impact Statement (3.26) prepared for Dome/Esso/Gulf. This statement was submitted to the Canadian Government in 1982 in support of a start on oil production in the Canadian Beaufort Sea. These concepts included consideration of Arctic Production Loading Atoll (APLA) type islands (Figure 3.16) where enclosed harbors are created between two CRI type elongated islands.

3.2.2.3 -Concrete **Island Drilling System Super Series**

Glomar Marine Development has studied (3.19) a Concrete Island Drilling System Super Series, often called the Super CIDS. The structure (Figure 3.17) adopts a modular “brick” concept in that the major portion of the base structure is composed of stackable concrete brick-like elements. The basic concrete modules are typically 234 ft (71 m) square with heights that can be varied. Concrete module heights of 32 ft (10 m) and 44 ft (13 m) are reported in Reference 3.19. The corners of the modules are chambered. The modules are designed in honeycomb form with multiple cylindrical cells. The structure has an optional steel mud mat base which may be needed in some instances for load distribution on poor soils. The concrete modules are surmounted by a pair of steel barges which carry the drilling package. The barges can also be used for storage.

3.2.2.4 – **SAMS**

Sohio Petroleum developed a design for an Arctic Mobile Structure (SAMS) shown in Figure 3.18. This concept consists of an octagonal prestressed concrete barge supporting steel spud piles to develop transverse shear strength in addition to base friction or cohesion. The base is equipped with slots through which 7 ft (2 m) diameter steel piles will be driven as deep as 40 ft (12 m) below the mudline (3.11, 3.27).

3.2.2.5 – **BWACS**

BWACS (BWA Caisson System) is a cellular concrete caisson (Figure 3.19) proposed for use in the 30 to 70 ft (10 to 20 m) water depth range in the Beaufort, Chukchi, and Bering Seas (3.28, 3.29). The caisson measures 400 ft (122 m) across corners and has a minimum freeboard of 45 ft (14 m). To resist ice loads, it is water ballasted up to the underside of the deck. This enables the structure to be easily relocated without having to handle sand ballast. The structure needs no seabed preparation to function in moderately strong soils, but a wick drain installation system has been incorporated inside the structure to assist consolidation of weak seabed soils as described in Reference 3.29. The structure is licensed to Zapata Offshore Services of Houston, Texas.

3.2.2.6 -Stacked Annular Caisson System

A stacked caisson system for year-round drilling in 13 ft to 65 ft (4 to 20 m) of water was developed by the Anglo Energy/Nabors Drilling group (Figure 3.20). It has an octagonal self-contained upper drilling barge, a mid-section and a base caisson. The principle is to locate it on a dredged berm if necessary, infilling the center core with sand and using as in any of these sections as water depth demands. Internal sand is dewatered to increase its shear strength. A combination of steel and concrete has been developed to provide stronger composite action against ice forces. The platform base is 425 ft (130 m) across (3.11).

3.2.2.7 -Concrete **Production Island for Norton Sound**

Exxon developed a concrete production island concept for the 30-100 ft (10-30 m) water depth range and first-year ice conditions in Norton Sound, Alaska (Figure 3.21). The concrete caisson has a hexagonal base with the deck elevated on a support frame to keep it clear of possible ice rubble pile-up and also provide easy access to the base. The base diameter will be about 450 ft (137 m) in weak soils. The structure would be towed out as an outfitted single unit and can be infilled with sand or water after installation (3.11), depending on local soil conditions.

Other forms of concrete and steel production platforms, including a 152 m x 30 m concrete barge have also been developed in joint-industry studies for this area (3.30).

3.2.2.8-Concrete Gravity Base Structures for the Bering Sea

Exxon has conducted several studies to assess the applicability of tower shaped structures in the Bering Sea similar to those currently used in the North Sea (3.9). The water depth range, is 300 to 600 ft (100 m to 200 m) and earthquake forces have to be considered in addition to a severe wave environment. North Sea production platforms were studied parametrically.

The first version shown in Figure 3.22 is a conventional three-legged form designed for a water depth of 300 to 500 ft (100 to 150 m), moderate ice forces and strong seabed soils. The second type is a single tower version which is suitable for weaker seabed soils (Figure 3.23). A further single tower version equipped with an ice breaking cone (Figure 3.24) can resist significantly larger ice forces in weak soils and deeper water.

3.2.2.9 – Floating Arctic Caisson

A different approach was adopted by Exxon in a proposal for a floating drilling, production and storage caisson for arctic waters as described in Reference 3.31. This structure (Figure 3.25) consists of a cylindrical concrete caisson, with enlarged base, and an hour-glass shaped surface piercing configuration. The caisson can be moored to the seabed by an array of mooring lines.

A novel feature of this proposal was the provision of a heave inducing mechanism to augment the dynamic heave response generated by movement of ice past the structure. This induced heave would be created using vertically oriented long stroke jacks reacting against vertical mooring lines. A second unusual feature was the use of the hour-glass surface piercing shape to create a downward breaking mode for the ice. It was felt that downward breaking was more efficient than upward breaking as movement of the broken ice past the structure was facilitated by the lubricating qualities of the water. In addition, adfreeze of the broken ice to the structure was reduced.

3.2.2.10 – Iceberg Resistant Structures for the Canadian East Coast

For the Hibernia Field, off Newfoundland, Mobil has had extensive studies carried out for a large concrete gravity structure capable of sustaining the impact of a major iceberg. Various schemes for resisting the kinetic energy of impact have been studied. These include a structure having star points or a serrated circumference, to intercept the iceberg and absorb its energy in local crushing. Another concept embodies a separate concrete ring fender designed to move under extreme impact loads (Figure 3.26). After the iceberg has passed, it is proposed to refloat the fender so that it can be moved back into position (3.30). The basic structural configuration included in the initial tender (1989) for the concrete base for the Hibernia platform is shown in Figure 3.27.

Other concepts proposed and studied for the Canadian East Coast are concrete caissons seated on an underwater embankment of rock and a stepped pyramid, designed to intercept a berg at a lower elevation, thus reducing the overturning moment and also absorbing some of the impact energy by shearing the ice horizontally (Figure 3.28 and Reference 3.32).

3.2.2.11-Oceanographical and Sea Ice Research Platform

A concrete gravity base monotower, similar to that shown in Figure 3.23 except that it has an underwater transition cone to a circular base, is presently being designed for use in 100 ft (30 m) water off the northeast coast of Hokkaido, Japan. The location is in the southern part of the Okhotsk Sea where the southern boundary of sea ice formation in the northern hemisphere lies. The structure will be used as a central facility for research, studies and development regarding meteorology, oceanography, biology, marine and ice engineering, inshore fisheries and aquaculture. The concrete base supports facilities for conducting research activities, meeting rooms, living quarters, dining facilities, maintenance shops, communications, exhibition areas, and helideck. The concrete base also contains a promenade gallery which is at the outer periphery of the base, approximately 10 ft (3 m) above the seafloor. The gallery has windows along its length that look out onto the sea floor from which observations of underwater activities can be made.

The concrete base will use lightweight concrete in the upper column and in the transition cone. The circular base which will be made from normal weight concrete. The base has a diameter of 130 ft (40 m) and utilizes steel skirts. The support column has an outer diameter of 20 ft (6 m). Sand ballast is added to the structure to increase the resistance to sliding and overturning.

3.2.2.12 -Amauligak Production Platform

Gulf Canada has had extensive studies carried on for a snad cored production platform for the Amauligak field, in the ice shear zone of the Mackenzie Delta. This proposed platform is currently designed to be a concrete structure, with either a concrete, or a steel/concrete composite peripheral ice resisting wall. The structure would be positioned on top of a submerged sand berm (3.34).

3.3 – New Developments

3.3.1 -Steel/Concrete Composite Structural Systems

In recent research projects, steel and concrete have been combined to form composite structural systems to achieve strength combined with reduced structural weight. The application of composite construction appears to be especially well suited for the outer walls of arctic structures which will be exposed to intense ice pressures. Reference 3.33 contains a number of research reports that discuss 1) the utilization of composite construction, and 2) the strength of steel/concrete composites to simulated ice pressure loadings.

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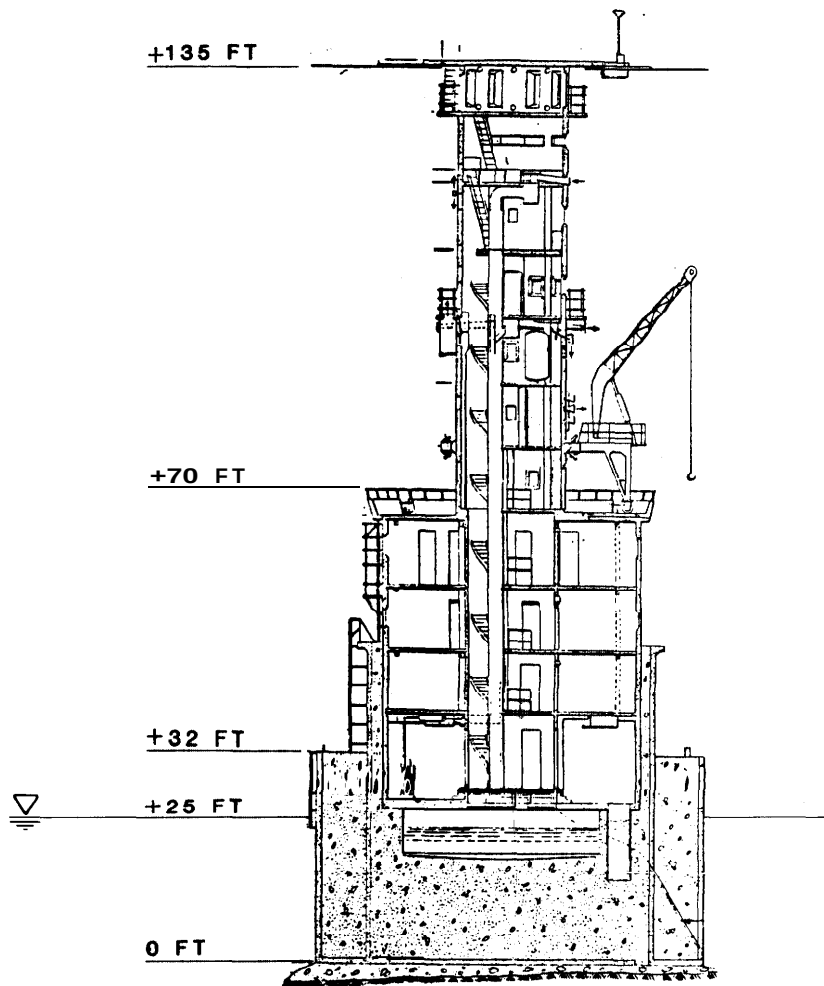


Fig. 3.1-Typical Scandinavian lighthouse

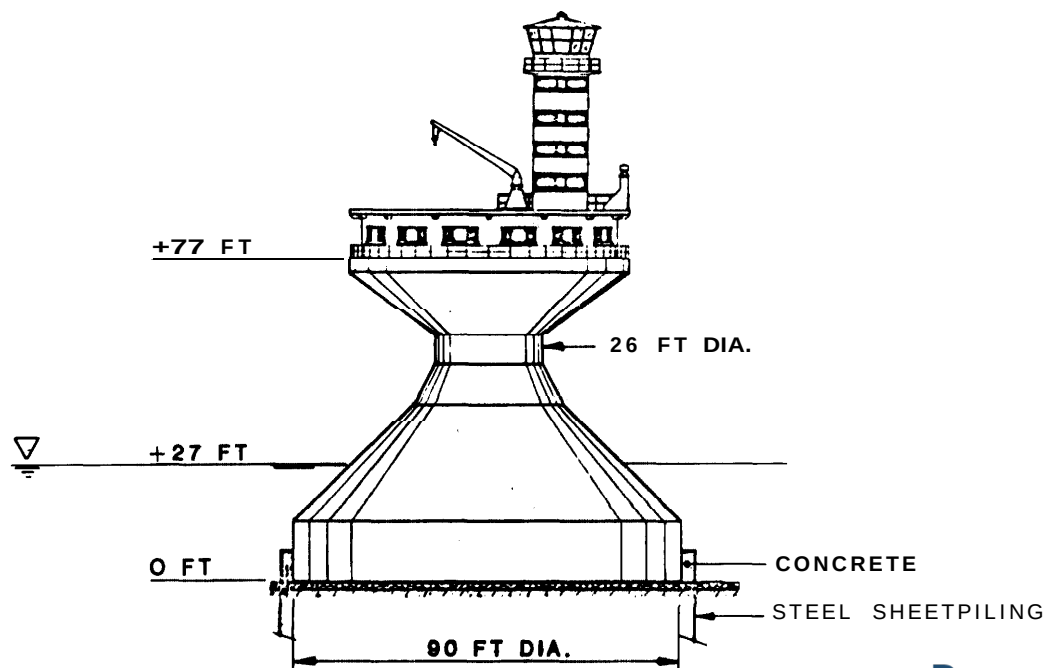


Fig. 3.2--Prince Shoal lighthouse in the St. Lawrence River built in 1963

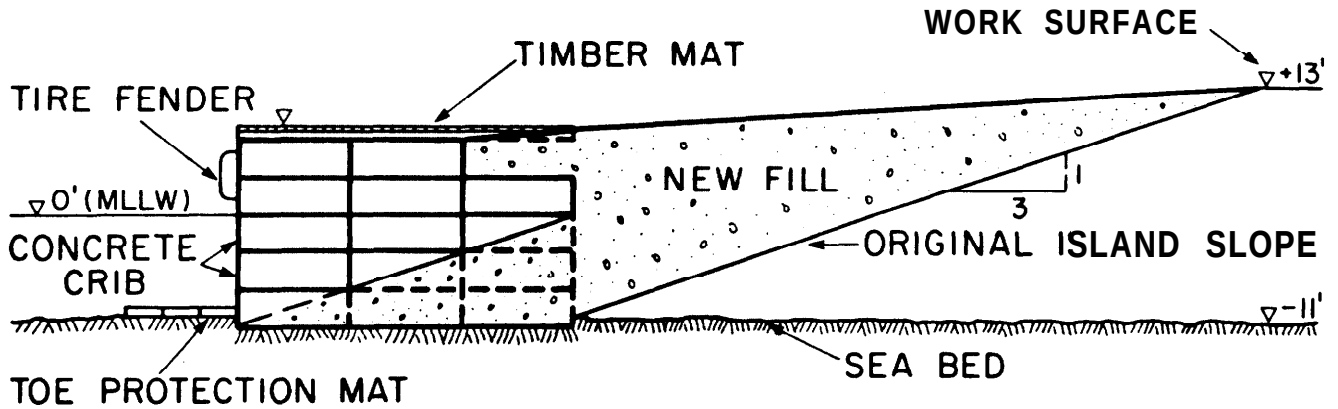


Fig. 3.3--Sohio's Arctic concrete pier configuration, 1980-81

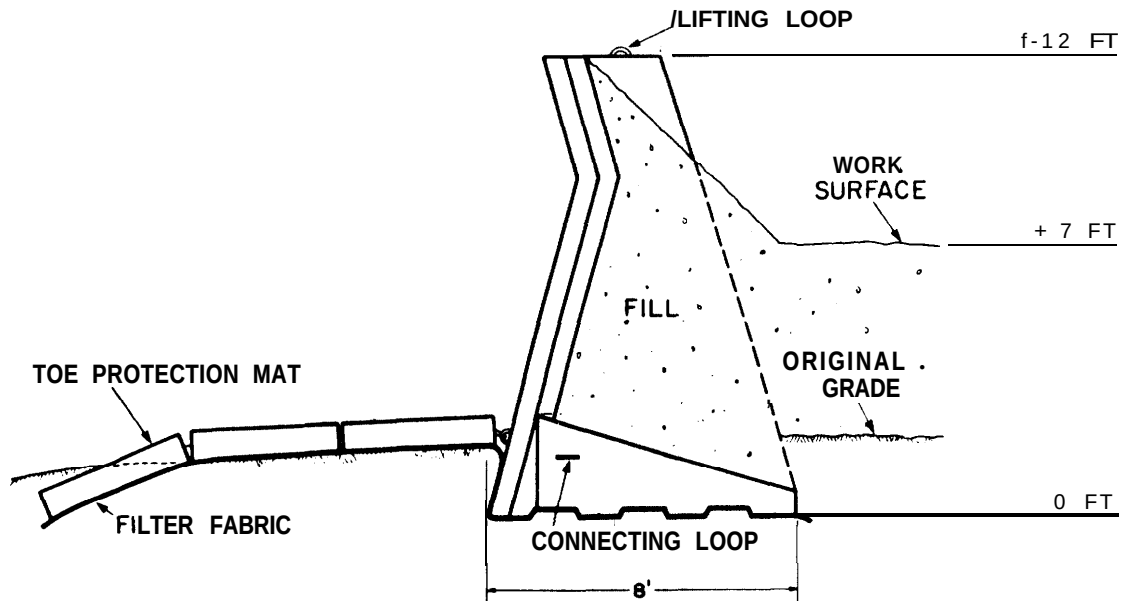


Fig. 3.4--Sohio's precast concrete seawall and slope protection, 1980-81

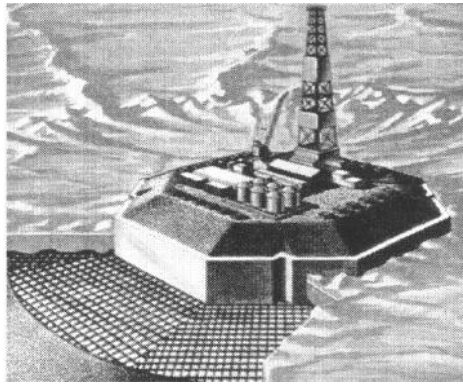


Fig. 3.5-Tarsiut caisson retained island in the Canadian Beaufort Sea, 1981
Photo courtesy of Dome Petroleum, Ltd.



Fig. 3.6--Super C.I.D.S
Photocourtesy of NKK America, Inc.

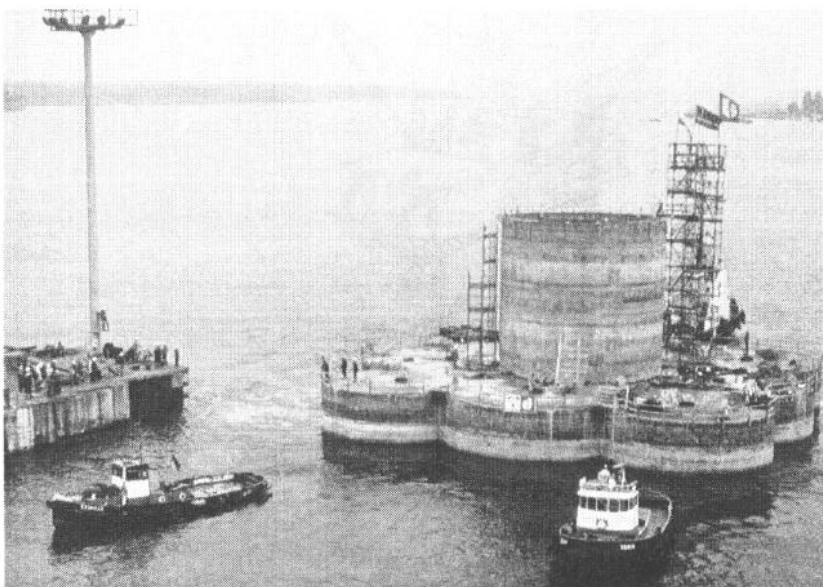


Fig. 3.7.--Texaco's platform for the Sea
Photo courtesy of Petroleum Engineer International Magazine

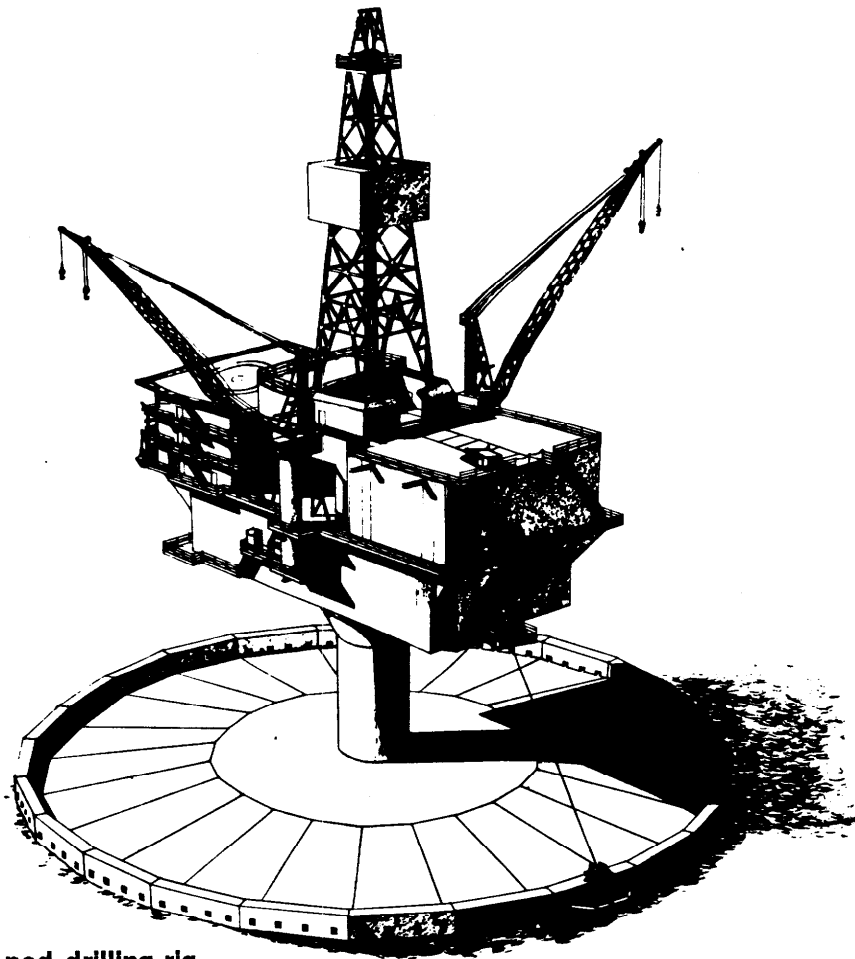


Fig. 3.8--Monopod drilling rig

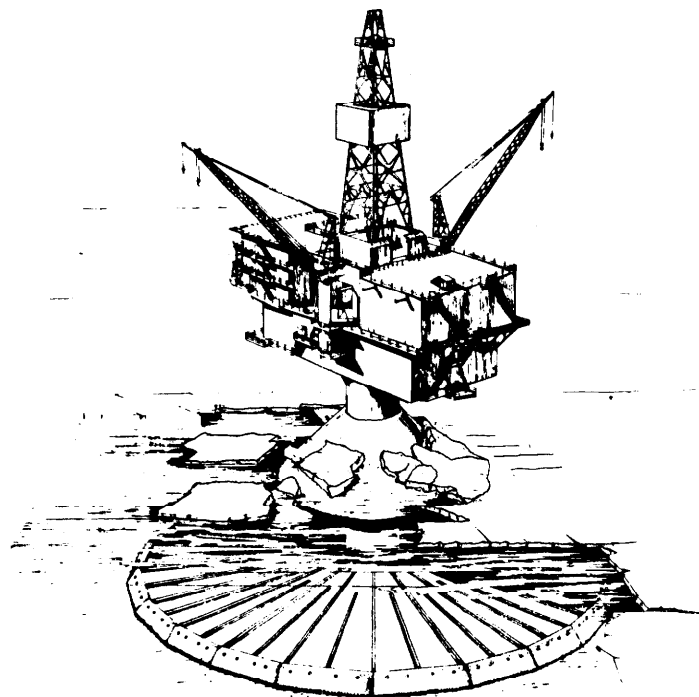


Fig. 3.9--Fixed cone drilling rig

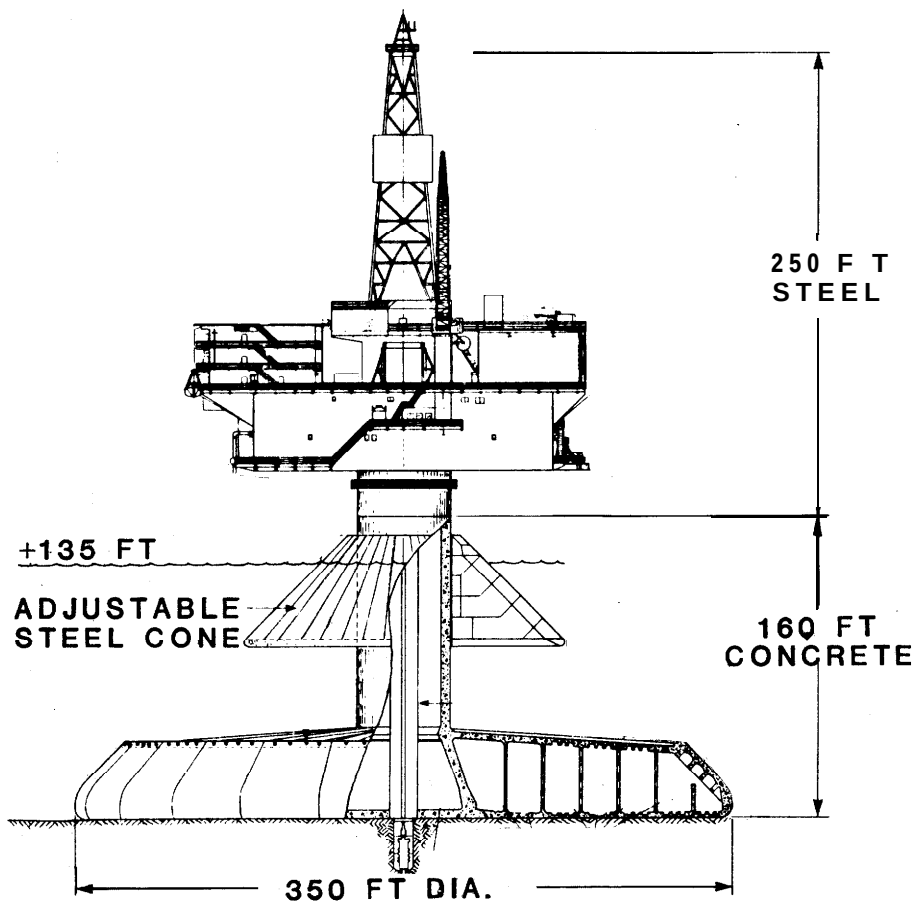


Fig. 3.10.-Adjustable monocone drilling rig

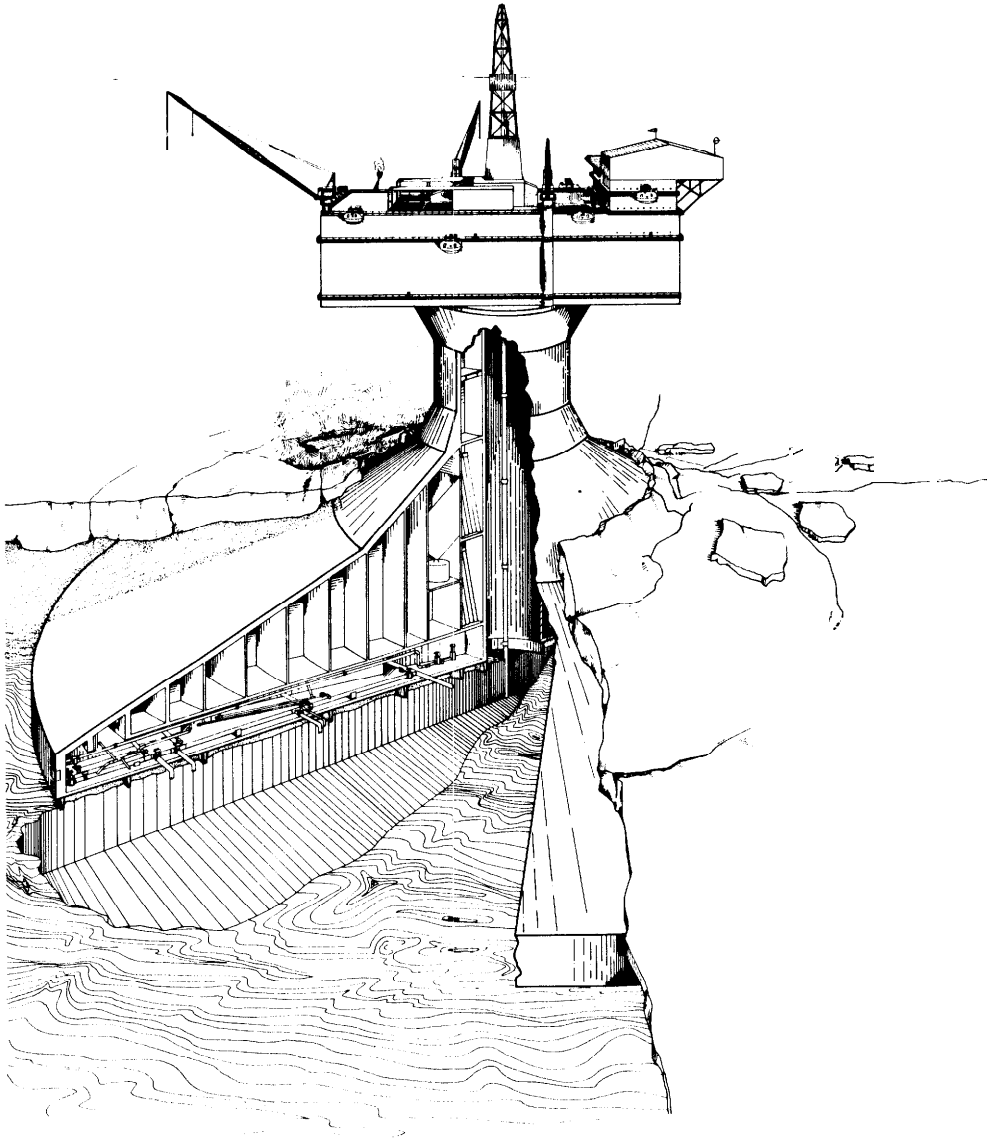


Fig. 3.1 I--Arctic cone exploration structure (ACES)

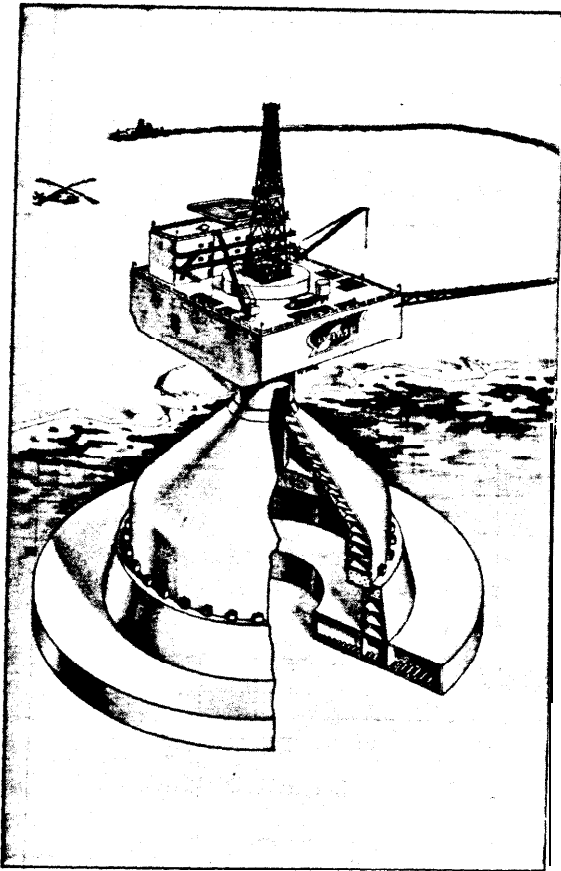


Fig. 3.12--Detachable
production monocone

Fig. 3.13--Crude off-loading
monocone for Norton Sound



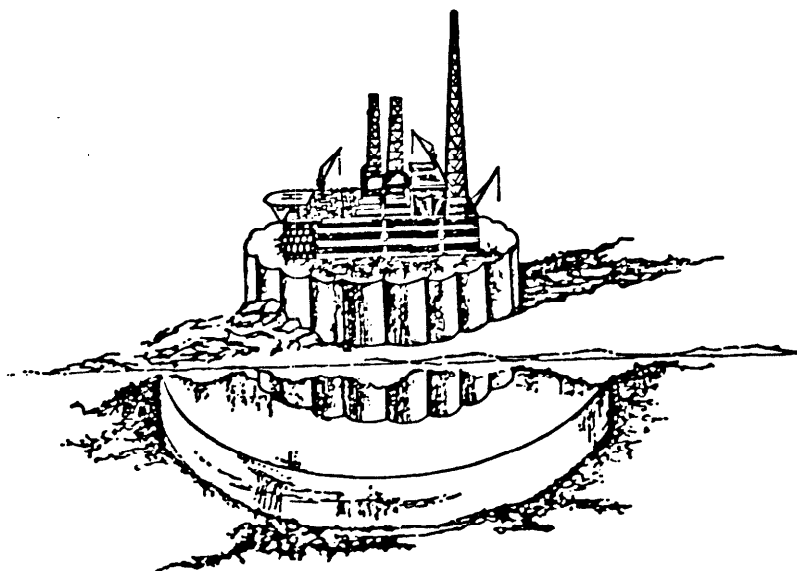


Fig. 3.14-Caisson on extended base

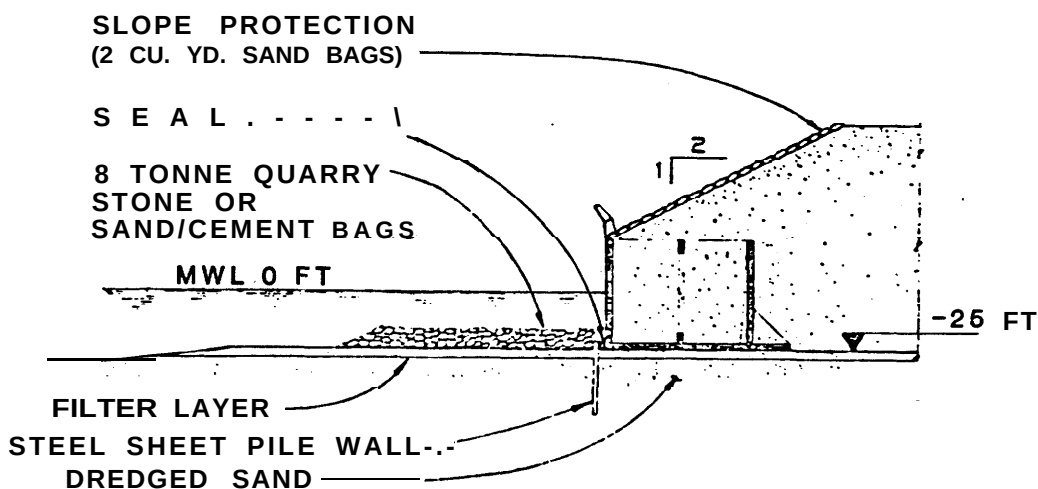


Fig. 3.15-Sohio's proposed caisson retained island

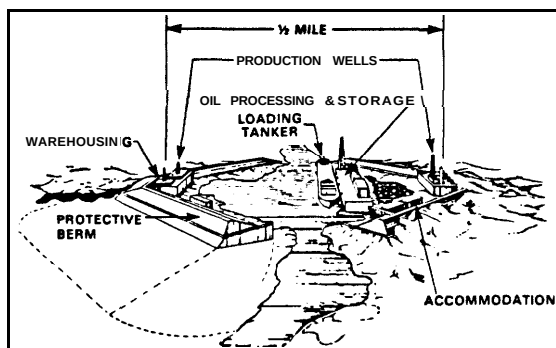


Fig. 3.16-I Arctic production loading atoll

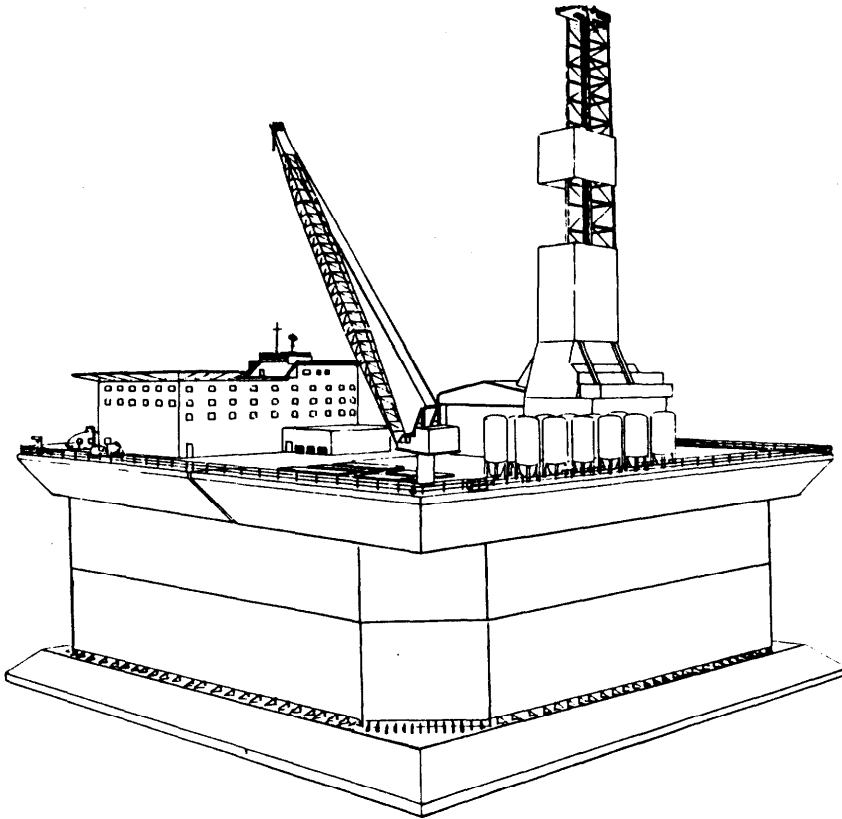


Fig. 3.17--Concrete island drilling system (CIDS)

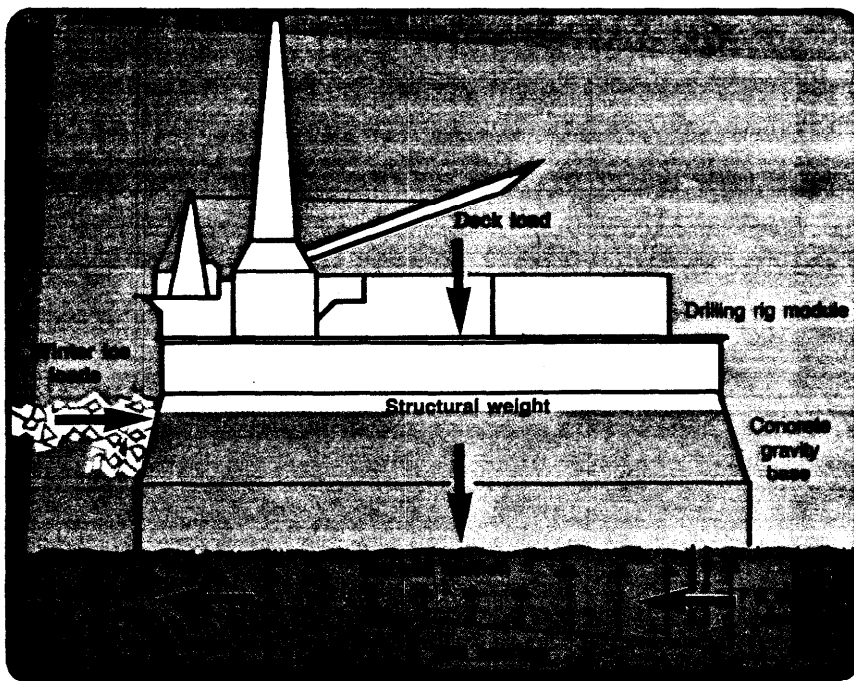


Fig. 3.18--Sohio Arctic mobile structure (SAMS)

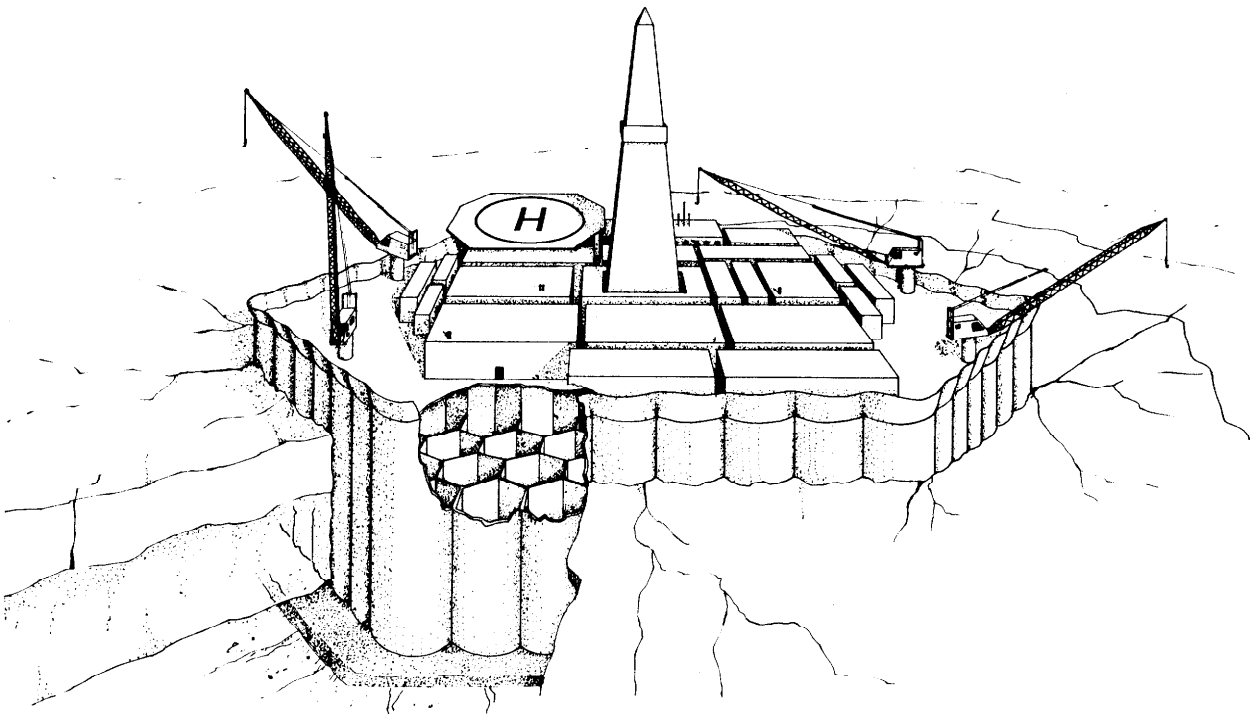


Fig. 3.19--BWA caisson system (BWACS)

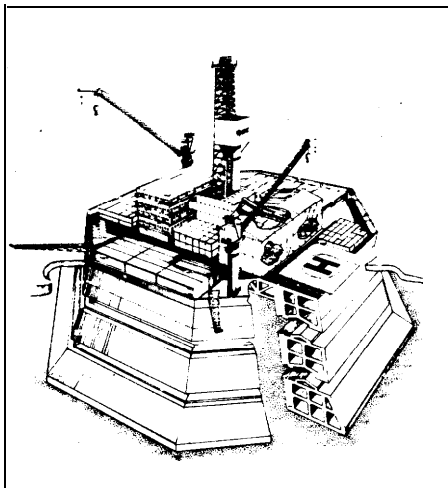


Fig. 3.20--Anglo Energy/Nabors stacked caisson

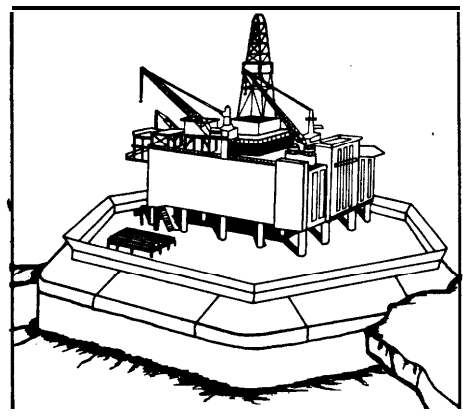
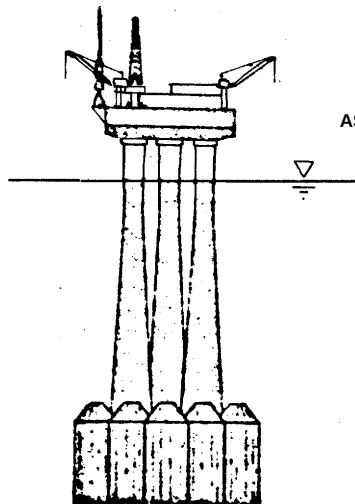


Fig. 3.21 --Exxon's concrete production island for Norton Sound



ASSUMED DESIGN CONDITIONS:

300 TO 500 FT WATER DEPTH

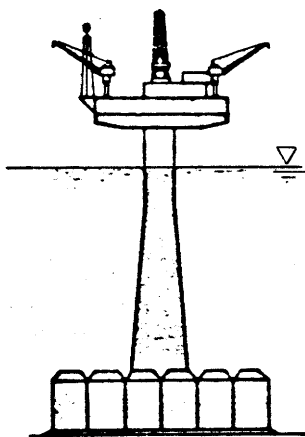
3 FT THICK SHEET ICE

30 FT THICK RIDGES

86 FT HIGH WAVES

0.2g PEAK GROUND ACCELERATION

Fig. 3.22--Multileg concrete gravity structure



ASSUMED SITE CONDITIONS:

300 TO 500 FT WATER DEPTH

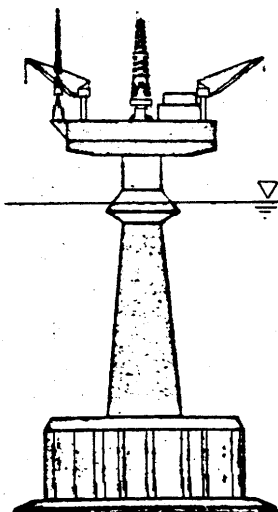
3 FT SHEET ICE

30 FT PRESSURE RIDGES

66 FT WAVES

0.2g EARTHQUAKE ACCELERATION

Fig. 3.23--Monotower gravity structure



ASSUMED SITE CONDITIONS:

300 TO 650 FT WATER DEPTH

4 FT SHEET ICE

60 FT PRESSURE RIDGES

90 FT WAVES

0.1g EARTHQUAKE ACCELERATION

Fig. 3.24--Monotower with ice breaking core

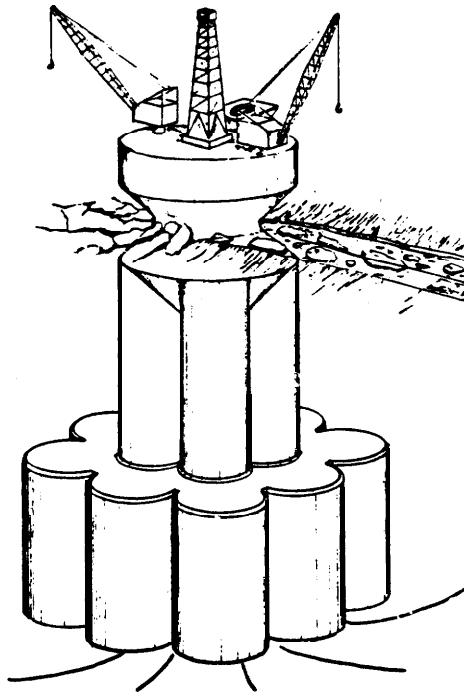


Fig. 3.25--Floating ice breaking caisson

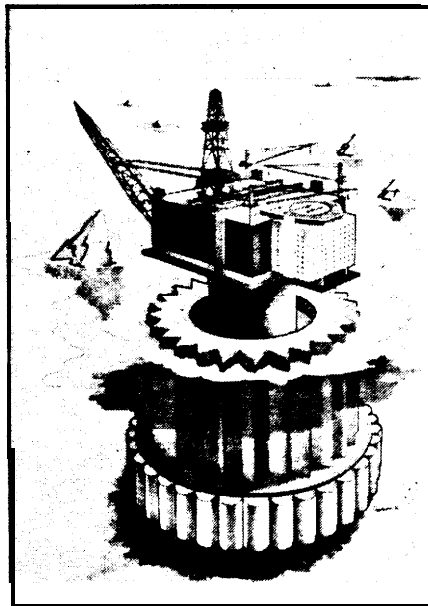


Fig. 3.26--Ring fender gravity platform

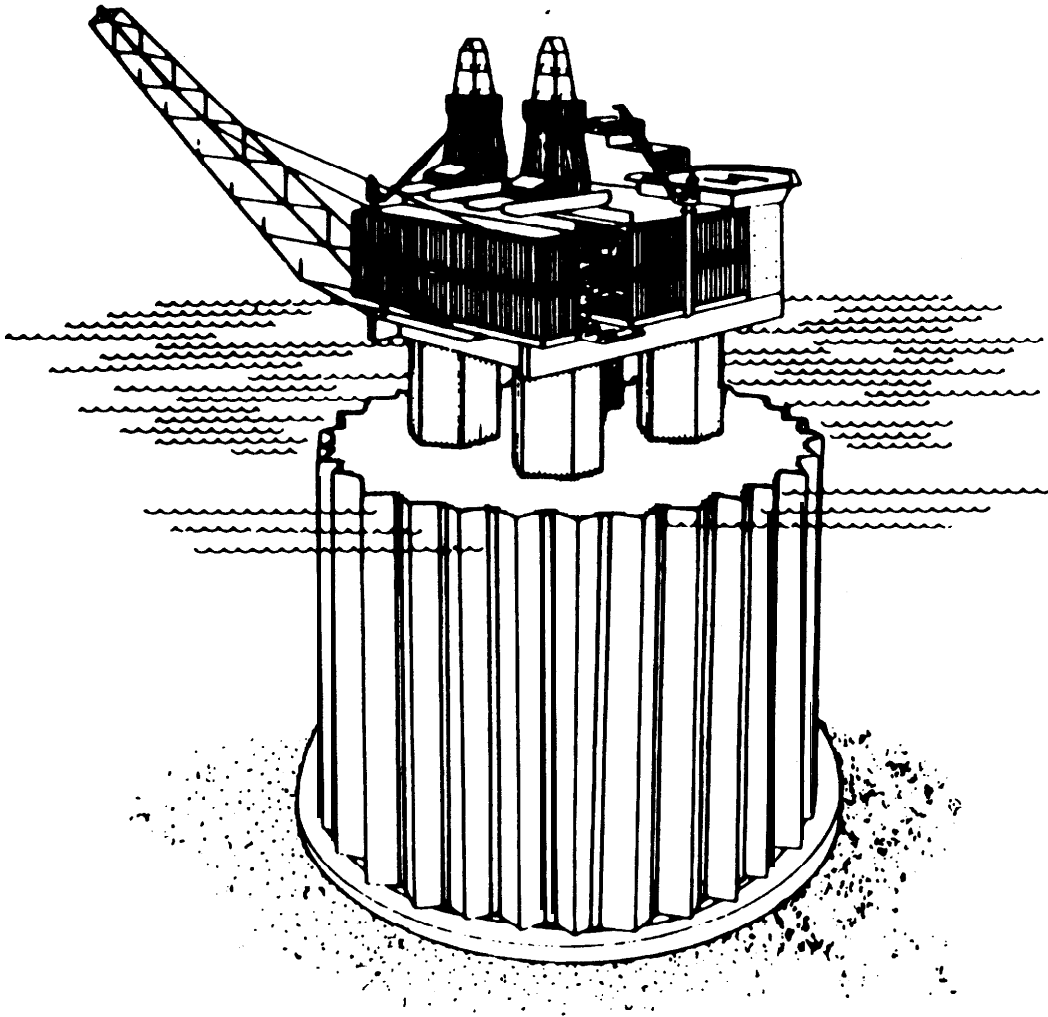


Fig. 3.27--Proposed (1989) Iceberg resisting production platform for the Hibernia development project

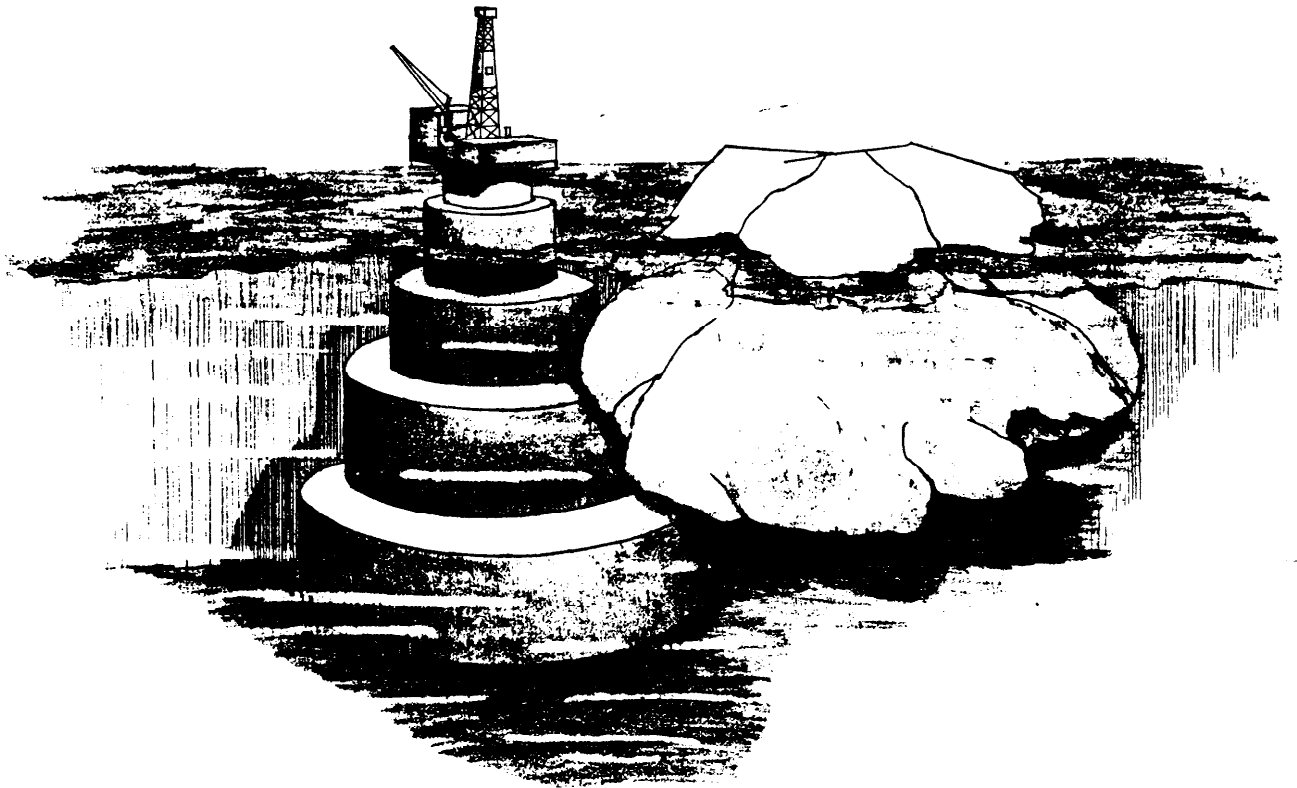


Fig. 3.28—The stepped pyramid concept