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Exploration and Production Concepts and Projects for the Arctic Offshore

by R.M.W. Frederking

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RÉSUMÉ

La recherche d'hydrocarbures dans l'océan Arctique a connu un essor considérable au cours des quinze dernières années. La présence d'imposantes masses glacielles nécessite l'utilisation de systèmes différents de ceux utilisés dans les autres régions où des travaux sont exécutés au large. Cette communication examine brièvement le milieu glaciel et l'interaction de la glace avec les systèmes d'exploration et de production proposés. L'auteur oppose les exigences de l'exploration à celles de la production et examine un certain nombre des systèmes proposés ou existants en soulignant leurs caractéristiques ou les problèmes qu'ils posent. Une importance particulière est accordée à l'expérience déjà acquise des systèmes d'exploration et de production; leur mise au point s'est effectuée d'une manière prudente, et il est important de souligner que la présence de la glace n'a occasionné aucun problème majeur.

IAHR Ice Symposium 1984
Hamburg

EXPLORATION AND PRODUCTION CONCEPTS AND PROJECTS FOR THE ARCTIC OFFSHORE

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ABSTRACT

The search for hydrocarbons in the Arctic offshore has increased substantially in the last 15 years. The presence of large ice features separates the systems required in the Arctic from those available for other offshore areas. The ice environment and the interaction between ice and proposed exploration and production systems are briefly reviewed. Requirements of exploration and production are contrasted. A number of the systems proposed or actually realized are examined, with attributes or problems noted. Particular emphasis is placed on actual experience with exploration and production systems. Development has been careful, and significantly there have been no major problems resulting from ice.

INTRODUCTION

The Arctic offshore has become an area of active exploration for hydrocarbons in the past decade and a half. The environment in the Arctic is generally considered hostile to people and their activities. A tremendous effort has been and continues to be expended on characterizing environmental conditions in northern polar regions and on developing engineering solutions that permit safe and economical operations in these offshore areas.

Why is there such a great interest in hydrocarbon exploration in the Arctic? A significant number of the sedimentary basins of the world (areas of potential hydrocarbon production) are located in this region and many of these extend into the offshore (Gaskell and Simpson, 1980). About a quarter

of the world's hydrocarbon resources could lie in the Arctic. The Alaskan and northern Canadian offshore alone may contain up to 10% of the world's petroleum reserves. Only a limited amount of exploratory drilling has been done in the Arctic (in the order of a few hundred wells), so a very great unproven potential exists.

The technology for offshore exploration and production has been developed to the point where production can be carried out in up to 200 m of water, even in areas with very difficult environments such as the North Sea. The presence of ice for a large part or even all of the year in Arctic waters presents entirely new problems and has been the prime factor in restricting offshore activities in these areas. Only now is this environment being understood and engineering solutions devised. This paper will examine aspects of the Arctic environment, review the solutions for exploration and production, both proposed and realized, and show how they relate to the conditions under which they must function. Experience with existing systems will also be reviewed.

THE ICE ENVIRONMENT IN OFFSHORE REGIONS

While ice is the primary factor unique to the Arctic, low temperatures, long periods of darkness and isolation are also significant. Attention has focused on the above factors, but wind, waves, and foundation conditions are equally important in the Arctic offshore, as in other offshore areas.

As a first step to evaluating some exploration and production schemes, the ice conditions have to be examined. Ice conditions include two factors: ice types and ice dynamics. The fundamental types of ice encountered in the Arctic are sea ice, formed by freezing of sea water; and glacial ice, which originates on land from snow falling on perennial snow fields. Glacial ice is usually in the form of icebergs but may also occur as ice islands. These ice islands could be considered a third type of ice, shelf ice, which occurs where glaciers meet sea ice. Sea ice is broadly classified according to age; that is, first-year or multi-year. Ice dynamics involves the thermal and mechanical response over time of the ice cover to the total climate, both marine and atmospheric. In certain areas level land-fast ice is formed, while in others the ice is deformed.

Sea Ice

First-year sea ice is formed from cooling and freezing of sea water. Under calm conditions, level, relatively uniform sheets of ice are formed by one-dimensional heat transfer upward through the ice cover into the atmosphere. The ice formed retains some of the salts from the sea water. The salinity of sea water in the Arctic is typically 30‰, while the average salinity of a first-year sea ice cover is 5‰ (Weeks and Lee, 1962). The top 5 to 30 cm of the ice cover typically has a randomly oriented granular grain structure and the remainder, a columnar-grained structure. It is common to find disruptions in this grain structure. Significant amounts of first-year sea ice are of frazil origin, having randomly oriented grain structure at any depth in the ice cover (Weeks and Ackley, 1983). The salt or brine content of first-year sea ice and its grain structure influence its strength and failure behaviour. A first-year sea ice cover can reach a maximum thickness of slightly more than 2 m under normal growth conditions (Bilello, 1961).

Mechanical working of first-year sea ice due to movements induced by wind or current can result in ridging or rafting, which produces geometrically larger ice formations. Rafting is more common for ice less than 30 cm thick, but it can also occur occasionally for ice up to 2 m thick. Pressure ridges are formed by compression or shearing action between ice plates. These ridges can be quite large; the extreme example reported had a sail height of 13 m and a keel depth of 50 m. Most first-year ridges have a sail height less than 6 m (Wright et al, 1978). Sail and keel slopes of ridges are typically 20°, so they have a substantial cross-section. The central core of ridges consolidates or refreezes, but only as thick as the adjacent first-year ice sheet. Nevertheless, first-year pressure ridges are a significant factor, simply due to their size and mass.

Sea ice that has survived one or more melt seasons is termed multi-year ice. In the course of a melt season, melt water on the surface flushes a large part of the brine out of the ice, resulting in much lower salinities. Multi-year ice above the waterline has salinities less than 1‰, while the lower part has salinities of 2 to 3‰. Undeformed multi-year ice can attain a steady state thickness of 2.5 to 5 m (Maykut and Untersteiner, 1971). Much multi-year ice is deformed, however, and thicknesses up to 10 m have been reported (Serson, 1972). Multi-year floes may also contain multi-year

ridges, with extreme sail height of 11 m and keel depths of 31 m (Wright et al, 1978). Furthermore, multi-year ridges are consolidated or refrozen through their entire thickness, so they present a formidable threat to any offshore structure.

Glacial Ice

Glacial ice originates on land from snow accumulating on perennial snow fields. The weight of the overlying snow compresses the layers underneath, sintering it and entrapping air within the ice structure. At a bulk density of 830 kg/m^3, the air bubbles are completely enclosed by ice. Further overburden pressure compresses the air bubbles, resulting in bulk densities approaching 910 kg/m^3. This range of densities defines glacial ice (Paterson, 1981). Icebergs originate primarily from the glaciers of Greenland; a few also come from the glaciers of Ellesmere and Devon Islands, and Spitsbergen. Icebergs as large as 2×10^7 t have been reported, but a size range of 10^3 to 10^6 t could be expected along the Labrador coast. The other large feature of glacial ice origin is the ice island, a tabular form up to 10 km in diameter and 30 m thick. Ice islands have their origin in the remnant ice shelves of northern Ellesmere Island.

Ice Dynamics

Ice dynamics in the Arctic relate to the circulation of the Arctic Ocean and local winds. Although the Arctic basin is ice-covered for the entire year, it is in continual motion. Ice movements are a few kilometres per day, with local variations an order of magnitude larger or smaller. The movement produces extensive mechanical deformation, which results in a mixture of first-year and multi-year ice known as the polar pack.

As Figure 1 shows, almost the entire ice cover within the Arctic Basin is in movement. The principle areas are the Beaufort Gyre, Transpolar Drift and East Greenland Drift. Many local movements are shown by the smaller arrows. Within the Canadian Arctic Archipelago and along the coastal regions of the Arctic Basin, there are, however, areas of land-fast ice. The extent of this area depends very much upon local conditions: water depth, prevailing wind direction, storm paths, current, presence of islands, and river inflows. In the Beaufort Sea, the land-fast ice edge extends out to a water depth of about 20 m. For water depths greater than 5 m, ridges are present and become more frequent towards the offshore edge of this zone. Grounding

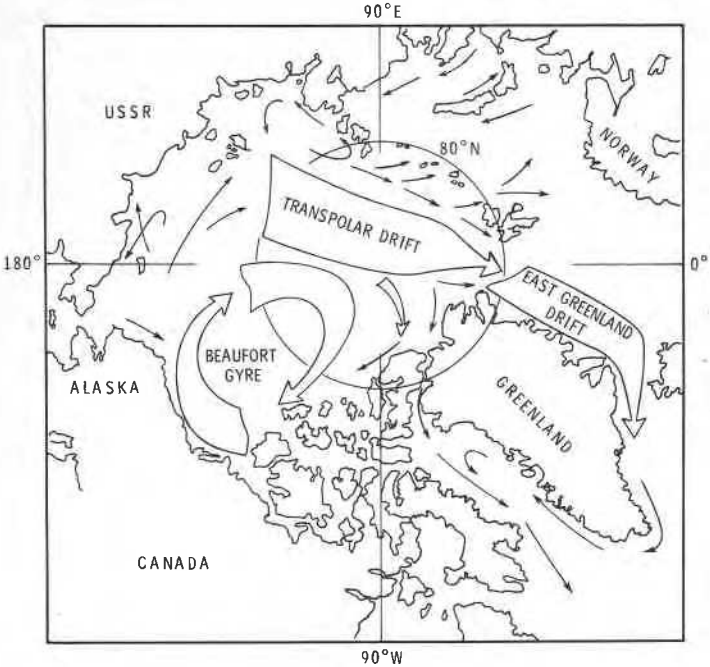

Figure 1. Ice movement in the Arctic Basin

of these ridges apparently tends to keep the ice cover in place. Land-fast ice, whether in near-shore regions or in island chains, is not completely immobile but can move from a few metres to a few hundred metres over a winter season. In some areas this land-fast ice completely clears out each summer, while in others it remains, becoming multi-year and may move only a few tens of metres during the summer. Between the land-fast ice edge and the polar pack is a transition zone, which accommodates the differential movements between them. This zone is highly variable, both spatially and over time.

Finally, an offshore structure and ice conditions are not mutually independent, at least on the local scale. The presence and nature of a structure can have a definite influence on the type of local ice conditions

generated; i.e., mode of failure of ice. The structure and the ice interact with each other.

Ice conditions, that is ice types and particularly the probable presence of extreme ice features and degree of movement, are a significant factor in prescribing schemes for petroleum exploration and production and primarily distinguish the Arctic offshore from other offshore areas. Other environmental factors, such as wind, current, waves and foundation materials, are also important. With the environmental picture established, the various projects and concepts for offshore drilling in the Arctic can now be explored.

REQUIREMENT FOR EXPLORATION VS PRODUCTION

Exploration and production activities, while sharing certain characteristics, have sufficient distinctly different requirements to merit separate consideration. Exploration drilling is a temporary activity. The prime objective is to obtain definitive geological information and to test the geological structure for producibility. Such an activity could last from a few weeks to several months. After the well is completed and tested, it is secured and abandoned. Therefore a permanent or fixed support structure for the rig is not needed. This limited exposure means that temporary, expedient, or "throw-away" support structures, such as grounded ice islands, floating ice platforms or sacrificial fill islands, can be used. An alternative system for exploration drilling would be portable or moveable and thus reusable, such as ice-reinforced drill ships, re-floatable caissons or special purpose floating structures. Because of the short-term nature of exploratory drilling, the risk of exposure to extreme environmental loads is less. Also it is possible to suspend activities in the event of extreme conditions.

All types of drilling require certain materials and consumables. Sufficient supply capacity or economical transporation of supplies to the site are important considerations. Drilling also requires accommodation of 50 to 100 people.

Production, on the other hand, is a long term activity, often extending over periods of 20 years or more. Therefore more permanent and durable facilities are required. Because of the much longer service life, there is

a higher risk of exposure to extreme environmental loads. Also the exposure is continuous and disruptions are less easily tolerated. With a production structure, there is also the requirement for storage and intermittent transport of the product or continuous transfer of the product to a suitable storage site or to shore. Production does not require the continuous presence of personnel, so little or no accommodation is required on such a structure.

The preceding discussion has focused on the operational phase of exploration and production systems. An equally important and critical phase is that of construction or tow-out and set down. Meeting the requirements of this phase has a major impact on the design of offshore systems.

EXPLORATION CONCEPTS AND PROJECTS

As pointed out earlier, an exploration system must be re-usable (mobile) or expendable. Three general categories of such systems can be identified: bottom-founded (gravity) structures, floating structures or artificial islands. Bottom-founded structures can be cylindrical, conical or caisson (see Figure 2). Floating structures can be either moored or dynamically positioned (Figure 3). Artificial islands can have natural slopes or they can be retained (Figure 4). Hybrids of these, for example, a gravity structure on a submarine berm, can be constructed. The distinction between bottom-founded structures and caisson-retained artificial islands is rather arbitrary. By definition, bottom-founded structures transfer load through their bases to the sea bottom, while a caisson-retained island transfers load primarily through fill material contained by the caisson. With bottom-founded structures and caisson-retained islands, a critical procedure is set-down of the structure on the sea bed. The time this takes establishes a weather window, i.e., times in which wind, waves, current or ice will not disrupt set-down. It is obviously desirable to shorten and simplify this procedure as much as possible.

Ice loads on these structures can be reduced by presenting a small cross-section at the water plane to the ice or by using inclined slopes to fail the ice in bending. Alternatively, the structure can be made sufficiently massive, with vertical faces to withstand the ice force and gain some benefit of reduced unit load with increased scale. These systems, their features and limitations are summarized in Table 1. A good review of

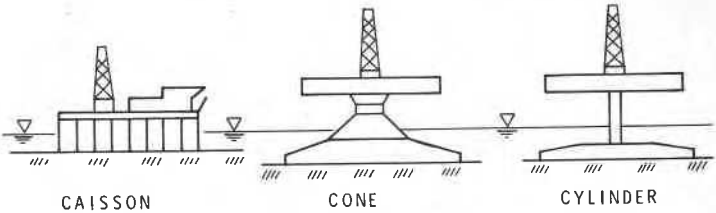

Figure 2. Bottom founded (gravity) structures

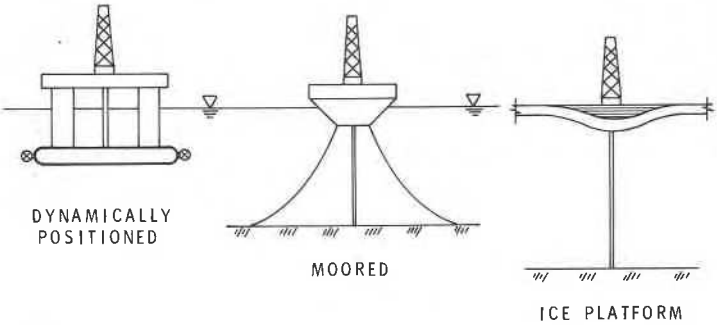

Figure 3. Floating systems

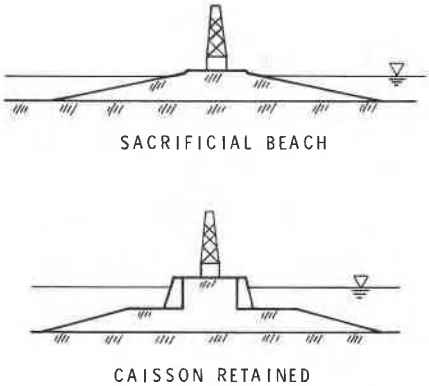

Figure 4. Artificial island systems

exploration and production systems has recently been made by Buslov and Krahl (1983).

Bottom-Founded Structures

Cylindrical type

These had their first application in the ice-covered waters of Cook Inlet in the Gulf of Alaska, where they have been used as production structures (Visser, 1969; Cloyd, 1968). Thus it is not surprising that one of the exploration structures proposed in the early 1970's for the Canadian Beaufort Sea was Esso Canada's (then Imperial Oil) monopod (Jazrawi and Davies, 1975). Intended for water depths up to 20 m, it comprised a 24-metre-long vertical cylinder 9 m in diameter, attached to a 97.5-metre-diameter base. The superstructure provided facilities for drilling, crew accommodation and supplies. The base featured 0.6 m deep shear keys and a perimeter ring to retain soil ballast for increased sliding resistance to horizontal ice forces. It was to be a steel structure, using water as ballast and intended for year-round use in the shallow (land-fast ice) areas of the Beaufort. The maximum design ice load was 135 MN for a 14-metre-thick first year pressure ridge at maximum consolidation. The structure was designed to fail by sliding at the base, thus avoiding damage under extreme loads. Ice monitoring to recognize extreme ice features and a sub-sea blow-out-preventor to permit safe securance of the well, were part of the system. The set-down phase was recognized as critical, so extensive model tests were carried out to examine stability, scour and loads. The concept went to detailed design stages, but was not built.

Another cylindrical type system is the monopod jack-up drilling rig of Global Marine (Anon, 1982). Intended for water depths up to 27 m in the Beaufort Sea, it comprises a rectangular base 78 × 65 m and a 9-metre-diameter by 27-metre-long column, which supports a 52-metre-square platform hull. The steel structure is ballasted with sea water. The position of the platform on the column can be adjusted with four moveable jacking legs. For set-down, the base is ballasted until the system floats on the platform hull; the base is then lowered to the sea bed, and the platform hull is jacked up to its operational height, where it is secured. Finally the jacking legs are raised. In this way a more controlled set-down can be achieved.

Conical type

A variation of the monopod, the monocone, was also proposed by Esso Canada (Jazrawi and Khanna, 1978). This structure, intended for use in water depths from 10 to 41 m, relied on a 45° conical collar to fail the ice in bending. For water depths less than 17 m, the structure would be placed in a dredged hole. The vertical cylinder and base were to be pre-stressed concrete, the conical collar and superstructure, steel. Both the base and the conical collar were ballasted with sea water. The cone, whose position would be adjusted over a range of 13 m, could be oriented to break the ice either upwards or downwards. The column was 15.2 m in diameter by 43 m long and integral with a 107-metre-diameter by 12-metre-thick base. In the upward breaking mode, the conical collar had a maximum freeboard of 4.5 m. The entire collar had a height of 17 m and a maximum diameter of 49 m. Heat was applied to the collar to prevent adfreezing of ice to it. A maximum global design ice load of 125 MN was specified for a 14 m ridge failing and riding up on the conical surface. A greater ice load could be generated due to adfreezing, but this was to be controlled by heating. A local design ice pressure of 8.3 MPa was applied over an area of 4.6 m^2. The bottom of the base was roughened, but otherwise flat. A sand blanket was to be laid down to assist transfer of horizontal loads from the base of the monocone to the sea bed. Model tests of the critical set-down and lift-off phase showed that tilt set-down was possible but not level set-down. This structure was taken to the design stage, but has not been built.

Another conceptual design is Chevron's Arctic Mobile Drill Structure (AMDS) (Hancock et al, 1979). The steel conical structure with a 75-metre-diameter base was intended for water depths of 6 to 18 m. Heating was to be provided on the upper part of the cone and the vertical column to control ice adfreezing. A shallow skirt around the base was to improve sliding resistance. The water-ballasted structure was intended for the Alaskan Beaufort Sea, with level first year ice containing multi-year pieces.

The Arctic cone exploration structure (ACES) is designed for use in water depths of 15 to 33 m and moving pack ice with 20-metre-thick ridges. The cone is designed to produce bending failure in larger multi-year ice floes and to have a sufficiently large diameter (168 m) to develop sliding resistance to ice forces. The structure is lightweight pre-stressed

concrete, with a steel superstructure. Ballasting is with sea water. This concept has been taken to the detailed engineering phase.

Somewhat similar in shape, but intended for deeper water, was Gulf Canada's steel mobile Arctic gravity platform (Wasilewski and Bruce, 1981). This is a mixed cone/cylinder structure. The design water depths were 20 to 50 m and base diameter 160 m. The cone was 45°, with a 70° cone transition to the vertical column. For water depths up to 30 m, the ice would fail by bending on the 45° cone, for water depths 30 to 40 m, by combined bending and crushing on the 70° cone, and for greater water depths, by crushing on the vertical column. Ice conditions for these water depths would include first year ice, ridges and large multi-year floes. Water was used for ballast. A special feature was radial ribs on the base between which sand could be placed to improve sliding resistance. Again, a matter of particular concern was the set-down/lift-off operation. For water depth up to 30 m, tilting could be used but the preferred method is a multi-point anchor system, which allows level set-down in water up to 50 m deep. This, like all conical systems, faces the basic set-down problem of instability due to reducing water plane area. A conceptual engineering study has been done on this system but it has not been built.

Caisson type

The first caisson structure concept to be realized is the single steel drilling caisson (SSDC) of Dome Petroleum. It is constructed from a former supertanker (VLCC). The bow and stern were removed, leaving a 162-metre-long by 53-metre-wide structure, which was substantially strengthened, including a one-metre-thick concrete layer behind the outer hull. The structure is set down at a 9 m draft on a berm. The outer walls are all vertical, with a 16 m freeboard along the sides. Sections are cantilevered out over the ice at the bow and stern to provide more deck space. Crew accommodation, drill rig and consumables are all stored on board. The structure is ballasted with water. With the vertical walls, particular attention must be paid to protection against wave-induced scour on the berm adjacent to the structure. The structure was first used in autumn, 1983, at the Uviluk P-66 location in 25 m of water in the Beaufort Sea. This location was in the transition zone and a rubble field formed around the structure. The rubble was surface-sprayed to increase its stability, thus reducing ice loads on the SSDC and providing a pad from

which a relief well could be drilled if necessary. The SSDC was used during the winter of 1983/84 to drill at Kogyuk in 28 m of water. This system has successfully withstood the dynamic ice of the transition zone and multi-year floe impacts.

The Arctic drill barge (ADB) is intended for shallow water (2 to 9 m) in the Beaufort Sea. Design ice conditions included two-metre-thick first year ice and 4 m ridges. The bottom of the structure is a steel barge 69 × 39 × 11 m, which can be ballasted onto the sea bed. The sides are sloped to encourage ice ride-up and heated to counter adfreezing. The steel superstructure stands on two columns to raise it above the barge. The concept is in the preliminary design phase. The concrete island drilling system (CIDS) of Global Marine has been realized in a version referred to as Super CIDS. The structure "Glomar Beaufort Sea I" was completed in the spring of 1984 and in November of 1984 it will commence drilling for Exxon at the Antares location in 15 m of water near Pit Point. The system comprises three components: a steel mud base that sits on the sea floor, a concrete "brick" mid-section that sits on the mud base and two steel deck storage barges adjacent to each other on the mid-section. The mud base is 90 × 95 × 7.6 m high and is ballasted with sea water. Its purpose is to increase the bearing area on the sea bed. The mid-section is a lightweight pre-stressed concrete honeycombed structure 71 × 71 × 13.4 m high, which is ballasted with sea water. The vertical walls of the concrete mid-section are in the zone of direct ice loads. The two deck storage barges, each 88 × 41 × 8 m high, accommodate drilling equipment, living quarters and supplies. The structure is intended for use in water depths from 11 to 17 m. Design ice conditions include two-metre-thick first year ice, ridges and multi-year ice. Spray flooding will be used to increase the stability of the ice rubble around the structure, thereby attenuating direct ice loads on it.

Another concept in the preliminary design phase is the caisson system (BWACS) proposed by Brian Watts and Associates, for water depth of 10 to 20 m off the northern coast of Alaska (Birdy, 1983). Design ice conditions include 18 m level ice and 5 m ridge or rubble accumulations. The structure is monolithic lightweight pre-stressed concrete with vertical exterior walls, hexagonal in plan (120 m across the corners) and 23 m high. The internal structure is composed of hexagonal cells ballasted with water.

Particular attention has been paid in the design to drains to improve foundation performance. The structure is large enough to have provisions for nine months and to drill three 4000-metre-deep wells.

The Sohio Arctic mobile structure (SAMS) is octagonal pre-stressed concrete, intended for 12 to 18 m water depth in the Harrison Bay area of the Alaskan Beaufort Sea (Anon, 1984a). A special feature of the design is the use of short piles, which can be placed through the base to provide additional sliding resistance. The maximum ice load in the transition zone where the structure will be sited is expected to exceed 450 MN. The structure is 105 m across and 35 m in overall height. It is expected to be in place in 1985.

The mobile Arctic drilling structure is a conceptual design by Global Marine for the nearshore area of the Beaufort Sea (2-6 m water depth). The structure has a base 90 × 63 m, with sloping sides to cause the ice to fail in bending. Set in from this base is a pedestal, to be constructed from a section of an old supertanker. The structure would be ballasted with seawater. A feature of this concept is low cost.

A new concept from Bow Arctic Resources is a mobile Arctic island (MAI), to be constructed from an old supertanker (Anon, 1984b). The tanker would be cut into pieces and reassembled in a form suitable for application as a drilling structure. It would be usable in water depths up to 23 m. With internal reinforcing and incorporation of an ice fender, ice loads of 9 MN per metre of structure width could be resisted.

Floating Structures

Floating systems for exploratory drilling were initially used in Arctic waters for summer operations. In 1976, Dome brought three ice-strengthened drillships into the Beaufort area. An additional ship was added later to bring the fleet up to four. These drillships feature sponsons on the outer hull to provide a double-hull and ice class 1A, an eight-point mooring system with acoustic releases, fairleads to reduce ice contact with the mooring lines, and two thrusters to deflect ice floes and reduce ice friction. The ships were initially allowed to drill in the open water season only, but as experience was gained, operations were permitted into the autumn period as late as November. During this period ice was already

present and icebreaking supply boats were employed in ice management around the ships, particularly in October. At the same time, efforts were made towards the early break-out of the drill ships from their winter harbour at McKinley Bay, since drill sites in the transition zone were often ice-free or in open pack by early June. The resulting drilling season can be up to four months long. More than 15 wells have been drilled with these drillships, in water depths ranging from 23 to 68 m.

Based on their experience with drillships, Dome has put forward two concepts for advanced systems. The swivel drillship is intended for water depths 20 to 120 m and would operate with an extended season in the transition zone and year-round in land-fast ice with Class 6 icebreaker support. The unique feature of this system is a turret mooring swivel in the forebody of the ship. The rig sits on the turret and 16 mooring lines extending from the turret to the sea bottom allow the bow of the vessel to weathervane into the moving ice. Another variation was the round drillship, intended for year-round drilling in the transition zone with icebreaker assistance. The hull was 65 m in diameter, strengthened to Arctic Class 6 and saucer-shaped to reduce ice forces. Mooring lines were to be attached to a small central cone extending below the level of ice action. Neither concept has advanced beyond the preliminary design phase.

Mitsui has proposed two floating drilling structures. One, an ice resistant barge, has a turret anchored to the sea bed and an egg-shaped hull, which weathervanes into the moving ice. The hull is sloped to break the ice downward. Areas of application include severe ice or deep open water. The other proposal is for a floating rig inside an ice-free zone. Heat would be applied to maintain an ice-free annulus between a floating moored drill barge and a floating steel caisson. The rig would be used in the landfast ice of the Beaufort.

A concept put forward some time ago by General Dynamics was an Arctic drill barge to operate in the Beaufort Sea. A 45-metre-diameter conical-shaped floating platform is anchored to the sea bed with eight pre-tensional mooring lines. The structure could break 1.5 m level ice but icebreaker support would be an integral part of the system. It was intended for water depths from 20 to 200 m.

Gulf Canada's conical drilling unit named the "Kulluk" entered service in the Beaufort Sea in the summer of 1983 (Gaida et al, 1983). It is designed to operate in water depths from 24 to 55 m. The structure is an inverted cone with a slope of 30° to the horizontal and an outer diameter of 81 m. The final form of the hull is the result of extensive model testing. Ice fouling of the mooring lines was of particular concern. The solution was a reverse lip at the bottom of the cone and an ice deflection ring. Twelve mooring lines of 90 mm diameter can hold the unit on location in up to 1.2 m of level ice. The hull is strengthened to Arctic Class 4. Two 24,000 hp icebreakers and two 15,000 hp supply boats are used around the Kulluk to break up thick ice, large floes and ridges into more manageable ice features (Hnatiuk and Wright, 1984). Reconnaissance to recognize and identify hazardous ice features is important for management and safety of the operation. The first well drilled with the system at Pitsiuluk put it to a severe test. The Kulluk was exposed in early September to old ice with thickness of 2 to 3 m and ridges with thicknesses of 20 to 30 m. Using the entire ice management system, it was possible to cope with these conditions but it was eventually decided to secure the well and move to the Amauligak location. By early October the drilling unit was forced to move again by similarly severe ice conditions. In early November, the structure returned to the Amauligak location and operated in normal seasonal ice conditions until December 11. The system performed well and no damage was sustained by the Kulluk, even in the exceptionally severe ice conditions of 1983 (Loh and Stamberg, 1984).

Semi-submersibles

A concept for a dynamically positioned drilling system called the ice-cutting semi-submersible drilling vessel (ICSDV) was put forward by SEDCO and Sea-Log in the mid 1970's. An underwater cylindrical hull 79 m in diameter by 22 m high was attached to a 31 m long by 11.5 m diameter column, which passed up through the water plane to support a superstructure with drilling equipment and accommodation. A revolving cutting sleeve extended over a 20 m length of the column. Thrusters counteracted the tongue of the cutter and kept the unit on location in moving ice. Small scale field demonstrations showed that a full-scale version could theoretically cut through 12 m ridges at a rate of 0.5 m/s.

An ice-class semi-submersible (ICE MAIDEN) has been designed in Europe. Heat would be used to reduce ice adhesion and a mechanical system to break up the ice. Thrusters and a mooring system would be used to assist ice loading. The structure is intended for deepwater applications in the Arctic.

Another Arctic semi-submersible drilling unit has been designed by Mitsui for ARCO Oil and Gas Co. (Corona and Yashima, 1983). The structure is similar to a conventional semi-submersible, but has no struts or bracing passing through the water plane. The vertical columns are clear, but fitted with compound vertical cones to break the ice in bending. For water depths up to 20 m, the structure would be ballasted to sit on the sea bottom. For deeper water it would be moored. It is designed to resist 2 m level ice and ridges up to 25 m in depth.

Ice platforms

This type of floating drilling system has been extensively utilized in the Canadian Arctic Archipelago (Baudais et al, 1974). The primary requirement is that horizontal movement of the ice cover not exceed 5% of the water depth over the duration of the drilling period. This requirement is met in many areas of the Arctic Archipelago. The weight of the drill rigs used (5-20 MN) exceeds the carrying capacity of the natural ice cover, so a controlled surface flooding technique has been developed to build up ice thickness to the required 5-6 m over a 200 m diameter. Since the first exploratory well was drilled over the winter of 1973/74, over 30 wells have been successfully completed using this technique. In 1978 the technique was used at Drake Point in a demonstration project to drill a production well and lay a flow line bundle in a plowed trench to bring the product to shore (Palmer et al, 1979).

Artificial Islands

Sacrificial beach

Artificial islands have been used extensively in the Beaufort Sea for exploratory drilling. The first such island was for the Immerk B-48 well drilled by Esso Canada in the winter 1973/74. It was constructed in 3 m of water using a stationary suction barge. Sandbags provided slope protection and reduced the amount of fill required. Two summers were required to

complete the island. Construction techniques for other islands have included dredging in summer and winter hauling over the ice.

In the summer of 1976, the first sacrificial beach island was constructed in 8.5 m of water for the Arnak L-30 well. The slopes on these islands are of the order of 1:12 and require large amounts of fill, which is usually obtained locally. The construction of such islands was made possible by high capacity cutter suction dredges, such as the Beaver Mackenzie. Gravel islands have been built, particularly in the Alaskan Beaufort by hauling across the ice from borrow sites on shore. The deepest water to date in which an island has been constructed is 20 m at Issungnak. Experience with these artificial islands has been very favourable and no ice problems have been encountered. Generally a larger rubble field forms around the artificial islands as moving ice piles up on the shore and on submarine slopes around the island. This grounded rubble field carries ice loads into the sea bottom, reducing the load on the island itself. Erosion due to wave action has been a problem during the open water period. This has been countered with protective measures such as sandbags, nets and geotextile mats.

A variation of these islands is the grounded ice island. The first one was built in the Alaskan Beaufort. There has also been interest in building grounded ice islands in the Soviet Union using spray flooding. A regulatory requirement in the Canadian Arctic is same-season relief well capability, and the grounded ice pad is an economical solution to this requirement.

Caisson-retained islands

In deeper water the amount of fill required for an artificial island becomes very large; for example, Issungnak, in 20 m of water, required 5×10^6 m^3. The first caisson-retained island was Tarsiut, built in 1981 in 22 m of water. Four individual concrete caissons were placed on a berm, which came to within 5 m of the water surface. A special technique created slopes of 1:7 or steeper on the berm. Because of the steep slopes and high ice loading, suitable sand fill had to be brought from as far as 65 km. Altogether 1.5×10^6 m^3 of material were required. The caissons were ballasted with water and then infilled with sand, as was the central core. Special doors were fitted to close the gaps where the caissons joined. Several days of calm weather were required to set down the caissons and

completely secure them. The design called for armour rock on the berm at the toe of the caisson to prevent wave scour. It has been in place for three winters and has satisfactorily withstood ice loads. Some maintenance has been done each summer to counteract the effects of scour and erosion. The caissons are being removed this summer (1984).

Esso's Caisson Retained Island (CRI) has just completed a year of service in the Beaufort Sea. A well was drilled in 13.5 m of water at Kadluk over the winter 1983/84. Eight trapezoidal elements, held together in a 117-metre-diameter octagonal ring by tensioning cables, make up the caisson. The structure can be assembled in whole or part before tow-out. The caisson elements are ballasted with water and the core filled with sand. Ice loads are transferred from the flexible caisson to the sand core and in turn to the sea bottom. Set-down depth of the structure is 9 m and it has a freeboard of 3 m. Supplementary wave and ice deflectors bring the freeboard to 7.5 m. Drilling, camp and supplies are placed on the sand core. Lift-off is accomplished by loosening the tension cables and deballasting the caissons. The caisson can be either placed on a berm if water depth is greater than 9 m or set in a hole if it is less. The design ice condition is either 2 m level ice acting on the whole diameter or a three-metre-thick floe.

Gulf Canada's Mobile Arctic Caisson (MAC) now named "Molikpaq" will be entering the Beaufort Sea this summer (1984). The steel caisson structure is 29 m high, uneven octagonal in plan, 111 m across at the base and 81 m across at the top. Normal set-down depth is 21.5 m and with deflectors it will have 12 m of freeboard. A central core 72 m square is filled with sand. The drilling machinery and accommodation sit on a box girder deck, which spans the entire top of the caisson. Heat is supplied to the under-deck area and ballast tanks to prevent freezing of ballast water and the sand core. The unit will be used to drill a delineation well over the winter 84/85 on the Tarsiut structure in a water depth of about 25 m.

PRODUCTION CONCEPTS AND PROJECTS

A production structure must perform satisfactorily over a 20 to 30 year lifetime, in other words it has to be permanent. Because of the longer life, it is possible to amortise the cost of a more substantial structure. On the other hand, because of the longer life, the risk of encounter with an

extreme ice feature is higher. A choice has to be made between designing for an extreme case, say a thousand-year event, or designing for a lower condition and adopting a strategy of detecting extreme ice features, forecasting whether they present a hazard to the structure and developing a means of dealing with them. Also with a production structure, processing and transport or storage of the product have to be dealt with. Therefore some production systems require large storage capacity. This in turn can be an advantage, since it adds to the mass of the structure.

Some experience has been gained with production structures in ice-covered waters. In Cook Inlet, steel multi-legged or monopod structures have been employed since the mid-1960's. Ice conditions include level ice up to 1 m thick and first-year ridges. With a large tidal range, about 9 m, adfreezing of ice is not a problem. For design purposes an ice pressure of 2.1 MPa was assumed to be applied to the total diameter of the structure. The multi-legged structures are supported on 4.7-metre-diameter piles, while the monopod is 9.7 m in diameter. The structures are in about 20 m of water and all are fixed to the sea bottom with piles. Very recently (1983), two production platforms were placed in the Baltic off the German coast in water depths ranging from 15 to 25 m (Hollomon and Klatt, 1984). Ice pressure ridges and break-out from level ice were responsible for the extreme loading conditions. To withstand the ice loads, concrete structures were chosen.

The first offshore production from the Arctic will probably be from artificial islands in relatively shallow water. Exxon/Sohio have filed a plan for production from the Endicott reservoir in the Alaskan Beaufort Sea. The scheme includes four gravel islands in water depths ranging from 1.2 to 5.5 m, and a causeway connecting the central island to the shore. The first production schemes for the Canadian Beaufort will likely involve caisson-retained islands, for which there is extensive experience with exploration structures.

In general, production systems can be of the same three basic types as exploration systems, i.e, bottom-founded structures, floating structures and artificial islands. Islands would be suitable for shallow water (0-15 m), although they have been suggested for depths up 70 m. Structures would be suitable for intermediate water depths (15 to 100 m). Floating systems

would only be applicable in very deep water where fixed structures would be impossible.

Production structures can have the same three forms as exploration systems, i.e., cylindrical, conical and caisson. Cylindrical structures have been proposed for water depths of 90 to 150 m, where ice conditions are not too severe (i.e, 1 m level ice, 10 m ridges (Jahns, 1980)). The structures would be concrete, either three-legged, as the Condeeps, or monopods. A small cone at the water line could reduce ice loads. For shallower waters, conical structures have been proposed. These include a 30° cone standing on a berm 50 m below the water surface (Wetzel et al, 1980). This system was intended for water depths of 70 to 150 m off the Labrador Coast, where multi-year ice up to 20 m thick and icebergs are present. For the shallower water of the Chuckchi Sea, a concrete conical production structure has been proposed. A base 200 m in diameter and 35 m high would be used for oil storage. The intended water depth is 45 m. Shell proposes to use a controlled stiffness steel Arctic cone (COS-SAC) for a water depth of 13.5 m in the Beaufort area (Boaz and Bhula, 1981). It is designed for 2 m level ice and 15-metre-thick multi-year ice. The structure would be a water-ballasted cylinder 105 m across at the base and would have a 45° conical apron. A unique feature of the system is the flexible attachment of the cone to the cylinder for the purpose of attenuating ice loads. Another conical structure is the Arctic production monocone (APM) proposed by Dome/CBI and intended for 45 to 75 m of water in the Beaufort Sea (Stenning and Schumann, 1979). The cone and superstructure were designed to separate from the base in the event of the impact of an ice island. The base would protect the well head and the cone and superstructure would float off with the ice. A multiple leg structure with conical collars set below the waterline at a level to break thick ice features in flecture has been suggested for water depths of 9 to 18 m in the Beaufort Sea (Kliewer and Forbes, 1980). The legs are tied into the superstructure deck at the top and interconnected at the mud line. The structure could be fixed by piles if soil conditons require it. A caisson-type concrete structure has been considered by Exxon for water depths of 9 to 30 m in Norton Sound. The structure would be about 140 m across at the base so the ice loads could be resisted by the poor soils of the area. Soil conditions on the sea bed are a critical factor, since large loads are transmitted to the sea bed.

Only one concept for a floating production system has been proposed (Gerwick and Jahns, 1979). It is a cylindrical structure with a conical neck, which can break ice in flecture either upwards or downwards depending on draft. The structure, of reinforced pre-stressed concrete, would also have an active heaving system to assist in breaking.

The sandbag-retained islands used for exploration in the shallow areas of the Beaufort could also be used for production purposes (Dingle, 1982). Mitsui has proposed a sandtube-retained island. In a similar vein, but using a geotextile retaining bag, was the sandisle. There has also been a proposal from Norwegian interests to construct ice islands inside a steel shell and to provide refrigeration to counteract summer melting. The Toronto consulting firm Marshal Macklin Monaghan has proposed a deep water activity frozen sea bed (DAFS) structure. The octagonal-shaped steel caisson would have a sand core frozen to the sea bed with thermopiles.

CONCLUSION

A number of concepts and projects have been put forward for offshore exploration and production of hydrocarbons in Arctic regions. Numerous factors, primarily ice conditions, water depth and soil conditions, and the requirements of the operator, determine the optimum system for any particular location. Finally, system design is limited by the level of scientific and technical knowledge, including: ice conditions and behaviour, other environmental factors, the interaction process, the behaviour of the structure itself, and techniques for fabrication of steel or concrete structures, for dredging and for field operations. Scientific and technological capabilities are continually improving, as demonstrated by the presentations at this conference. Therefore, optimal solutions are in a constant state of flux and should not be constrained by existing practices.

The approach of designers in practice has been quite cautious. The extension of offshore exploration and production to Arctic waters has been a careful extrapolation of existing technology. Significantly, no disasters in the Arctic offshore have been due to ice. This indicates that designers have been conservative and no doubt well aware of the consequences of a disaster in the Arctic.

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TABLE 1 Types and features of exploration systems for the Arctic offshore

Types	Bottom-Founded	Floating	Artificial Islands
Forms	cylindrical conical caisson	conical ship-shaped	sloped vertical caisson
Anchoring	gravity piles or skirts	moored dynamically positioned	gravity
Re-use	portable	portable	portable or expendable
Material	steel or concrete	steel	steel, concrete, fill or combination
Water depth	15 - 150 m	25 - 200 + m	0 - 30 m
Ice conditions	first year ice ridges multi-year floes	first year ice < 1.5 m ridges	first year ice ridges multi-year floes

DISCUSSION BY: Dr. T. Carstens, River and Harbour Laboratory, Norwegian Hydrodynamic Laboratories, Trondheim, Norway

In one of your tables you presented a table of suitable structures for various tasks in various conditions. For floating structures the table somewhat categorically had steel as the only suitable material. Is this your considered opinion or is it a slip?

RESPONSE TO: T. Carstens

Steel was indicated for floating structures since to date, to my knowledge, all floating drilling systems have been steel. This is not to say that floating drilling structures could not be concrete. I think it must be recognized, however, that tradition, or perhaps human inertia, plays a role in the design of offshore structures and concrete structures will have to be better, not just comparable to steel ones. We have the example of concrete structures in the North Sea, which broke with the earlier practice of steel structures.

DISCUSSION BY: Prof. W.M. Sackinger, University of Alaska, Geophysical Institute, Fairbanks, Alaska

Could you comment upon the potential uses of bottom-founded articulated columns with moorings - including clump-weight moorings - and perhaps conical surfaces at the waterline - for deep-water locations and moving ice?

RESPONSE TO: W.M. Sackinger

For articulated column moorings in ice-covered waters the system would have to accommodate larger movements (in order to attenuate ice loads) than would such a system in open water. Conical surfaces at the waterline could help in reducing horizontal ice loads, provided the vertical ice load generated by the conical surface could be sustained by the structure.

DISCUSSION BY: Dr. D.S. Sodhi, US Army, Cold Regions Research Engineering Laboratory, Hanover, NH

Prof. Michel mentioned that an overall approach should be taken in designing structures for the Arctic. Will you please comment on the successes and failures of Arctic structures in standing up to wave action.

RESPONSE TO: D.S. Sodhi

I fully agree that a total approach has to be taken in designing offshore structures for the Arctic. There have been no failures caused by wave action, though it has caused operational problems during the construction phase. Also there has been some erosion of berms, which has been dealt with by maintenance. The influence of wave action was downplayed in comparison to ice loads, at least initially. This is not the case now.

DISCUSSION BY: Andrew Kendrick, German & Milne, Montreal, Canada

The paper has addressed a wide variety of concepts for drilling offshore. An equally important aspect of production is the transportation of the product. How does the author envisage this problem being treated in the event of major discoveries in the near future in the Arctic offshore?

RESPONSE TO: A. Kendrick

I would expect that major discoveries would see great pressure for transportation by tanker. I think this method is technically feasible, but there are political, social and environmental concerns. In projects of this magnitude, these latter factors often weigh more heavily than technical ones.

DISCUSSION BY: K.W. Pilarczyk, RWS/Delta Department, The Hague, The Netherlands

You have shown in your paper different artificial islands with different protective materials against waves and ice, i.e., gravel, sandbags, concrete, etc.

What is your experience regarding the behaviour of these protective materials during the break-up period? Is it possible that parts of the protection will be taken away within the ice mass?

What are the possible measures against it?

RESPONSE TO: K.W. Pilarczyk

During the initial part of the break-up period there is a melting of the ice at the shore line, effectively producing a moat around the island. Hence the protective materials are no longer exposed to ice and plucked away by it. After the ice cover starts to move it could dislodge material

by colliding with the island. This has not been a problem with exploration structures, which can sustain limited damage, but is more of a concern for long-term (production) structures. Dealing with the problem is a matter of economics, i.e., either designing a structure to be less susceptible to damage or accepting limited damage and correcting it with maintenance.

R.M.W. Frederking

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