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Offshore Oil in the Alaskan Arctic

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Summary. Oil and gas deposits in the Alaskan Arctic are estimated to contain up to 40 percent of the remaining undiscovered crude oil and oil-equivalent natural gas within U.S. jurisdiction. Most (65 to 70 percent) of these estimated reserves are believed to occur offshore beneath the shallow, ice-covered seas of the Alaskan continental shelf. Offshore recovery operations for such areas are far from routine, with the primary problems associated with the presence of ice. Some problems that must be resolved if efficient, cost-effective, environmentally safe, year-round offshore production is to be achieved include the accurate estimation of ice forces on offshore structures, the proper placement of pipelines beneath ice-produced gouges in the sea floor, and the cleanup of oil spills in pack ice areas.

Despite the high costs, the world's appetite for petroleum and petroleum products continues in a scarcely diminished fashion. In 1981 the world's total consumption was approximately 60 million barrels per day, of which more than 15 million barrels (or 25 percent) were consumed in the United States. Most of the oil available to the West comes from the physically accessible but politically unstable regions of the Middle East. In an attempt to discover more "secure" petroleum resources, the countries of the West have increasingly been forced to search in more remote and environmentally hostile areas. The possibility that the Arctic might be a major petroleum source received a great boost when in 1968 the Prudhoe Bay oil field, the tenth largest in the world to date, was discovered. Subsequent finds in Siberia, said to include the world's two largest gas fields, coupled with the discovery of the Sverdrup Basin gas field at 78°N in the Canadian Arctic Archipelago, have confirmed that the Arctic has vast oil and gas potential (*1*).

It is now believed that the areas with the highest oil and gas potential are the Alaskan North Slope and the adjacent Beaufort Sea off both the Alaskan and the Canadian coasts, Canada's Arctic Islands, the northern Soviet Union, and the Kara, Barents, and Norwegian seas. Although the Soviets have found such large onshore petroleum reserves that incentives for offshore exploration and production remain low, offshore activities of countries in the West are in full swing in the Arctic. One can obtain an indication of the cost of operating in the Arctic by noting that in the Beaufort Sea drilling costs are roughly $40 to $50 million per well as compared to $1.5 to $3 million for the average offshore well in the Gulf of Mexico. In this article we will focus on the region of most immediate concern to the United States, namely, northern Alaska and its adjacent seas.

Crude oil from the Alaskan Arctic currently flows down the Trans-Alaskan pipeline at a rate of roughly 1.6 million barrels per day. Of this amount, 1.5 million barrels come from the giant Prudhoe Bay field located on the edge of the Beaufort Sea and 100,000 barrels come from the Kuparuk Field, also located on land slightly to the west of Prudhoe Bay (Fig. 1). The combined production from these fields amounts to roughly 17 percent of the total U.S. production, constituting the largest "single" domestic source. By January 1984, just over 3 billion barrels of crude oil will have been pumped from the Prudhoe Bay field alone. Estimates of the remaining recoverable reserves at Prudhoe are 6.6 billion barrels or approximately one-third of the total proven reserves in the United States. Impressive as these figures are, producers indicate that by 1986 or 1987 production from the Prudhoe Bay field will peak, and it is expected that an initially rather precipitous drop of 15 percent per year will follow.

Will this signal the end of oil production from the Alaskan Arctic, or are other finds likely? If more oil is found, where will it probably occur and how much production might be expected? What problems are anticipated in producing oil in the hostile arctic environment, and what is the current state of our knowledge concerning some of these problems? In the following we will try to provide a general overview of the present situation in the Alaskan Arctic offshore region and peer into its future as best we can.

Oil and Gas Potential

The presence of petroleum in the Alaskan Arctic has been known since 1904 when oil seeps were found along the Beaufort Sea coast in what is now National Petroleum Reserve–Alaska. However, until the discovery of the Prudhoe Bay field in 1968, drilling was both sporadic and disappointing with the results essentially of only local interest. Since that strike, the level of geophysical exploration in the Alaskan Arctic has increased significantly (although geophysical coverage of many areas is still far from adequate). There are two reasons for the increased interest. First, the oil and gas potential of the Alaskan Arctic is now firmly established. Second, the Department of the Interior is opening vast

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areas of Arctic Alaska to oil and gas exploration through a series of major lease sales. In the Alaskan outer continental shelf region north of the Aleutian chain as of February 1984, four federal lease sales have offered a total of just under 7.4 million acres (1 acre = 0.405 hectare) for lease. Of this acreage, a total of 1.6 million acres were actually leased for $3.3 billion. In 1984 alone, 117 million more acres will be offered for lease in three major additional sales.

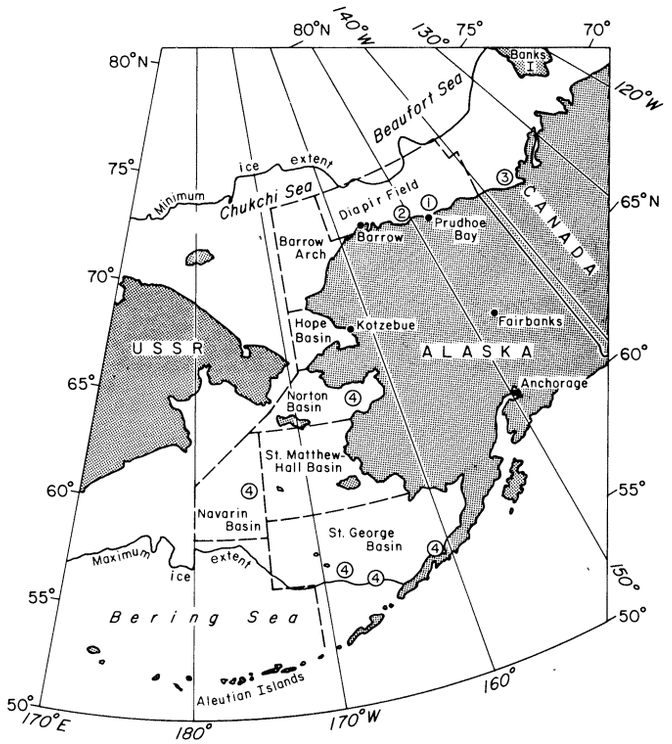
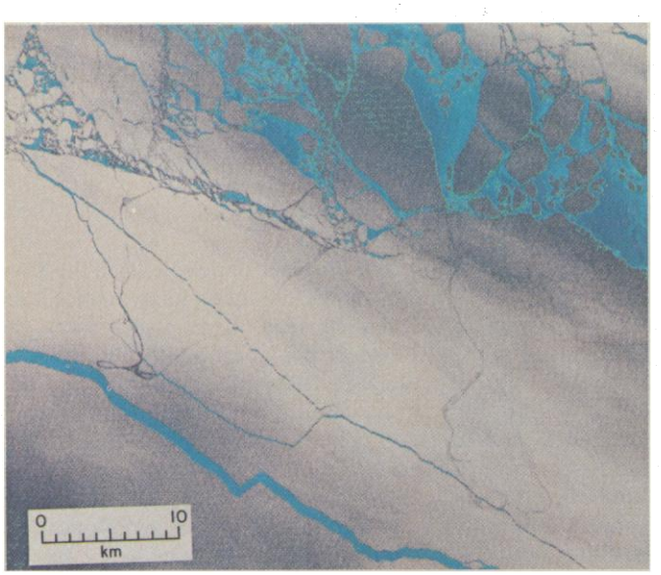


Fig. 1. Map showing the oil and gas regions on the Alaskan continental shelf north of the Aleutians. The boundaries of maximum and minimum ice extent are based on satellite observations over the period 1974 to 1982 (Navy–National Oceanic and Atmospheric Administration Joint Ice Center). The circled numbers indicate the general locations of present (or recent) offshore drilling, as follows: 1, north of Prudhoe Bay (Cross, No-name, Seal, and Tern islands); 2, Harrison Bay (Mukluk Island); 3, Mackenzie Bay (numerous artificial islands and structures); and 4, stratigraphic test (Continental Offshore Stratigraphic Testing) wells.

What is the current assessment of the oil and gas potential of the Alaskan Arctic? Both the U.S. Geological Survey and the petroleum industry have recently published independent estimates of this potential that are surprisingly similar (*2*). As of August 1980, 16.5 billion barrels of recoverable oil and oil-equivalent gas had been discovered. Industry spokesmen have estimated that an average of 44 billion barrels remained undiscovered, concluding that these undiscovered resources could comprise up to 40 percent of the total undiscovered recoverable oil and gas resources remaining within U.S. jurisdiction. In terms of undiscovered hydrocarbon resources, the Arctic is currently believed to be the single richest province in the nation.

Where is this undiscovered, potentially recoverable oil and gas located? Between 65 and 70 percent is believed to be located offshore beneath the shallow, ice-covered seas of the Alaskan continental shelf. The offshore regions (see Fig. 1) believed to have in excess of 1 billion barrels of oil equivalent (based on the average of the U.S. Geological Sur-



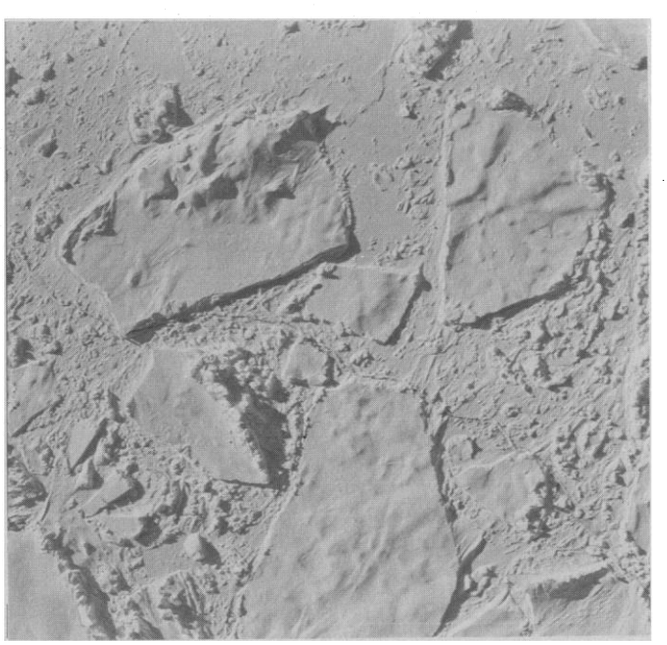


Fig. 2 (left). Tracks of Soviet icebreakers attempting to free several dozen cargo vessels trapped by unusually severe ice conditions in the Chukchi Sea about 80 km east of Cape Schmidt, Siberia, in October 1983 [Landsat image (composite of bands 5, 6, and 7) provided by the Quick-Look Facility of the Geophysical Institute of the University of Alaska, Fairbanks]. The color assignments are arbitrary: white, thicker ice (type and exact thickness indeterminate); green to light blue to dark blue, progressively thinner types of new ice in refrozen leads. The icebreaker tracks generally appear as grayish lines. The loops are produced when the icebreaker circles the trapped ship while attempting to break it free. Although Landsat imagery can be very useful in sea ice studies, it is limited by clouds and by darkness (except in the thermal infrared range). More useful is synthetic aperture radar (SAR) imagery, which is not limited by weather or light and can be used to obtain a variety of useful ice information (see the cover image). The National Aeronautics and Space Administration is currently planning to establish an SAR receiving station in Alaska to obtain ice information from SAR systems that are planned for launch by the European, Japanese, and Canadian space agencies (*34*). Fig. 3 (right). An aerial photograph of heavy pack ice in the Beaufort Sea. The angular floes are old ice, as indicated by their hummocky surfaces, which result from differential melting. The old ice is presumably 3 to 5 m thick. The first-year ice surrounding the old floes is between 0.3 and 1.5 m thick and contains many irregular ice fragments produced by the grinding together of ice floes. The crack running diagonally across the photograph indicates that this ice is undergoing deformation. The photograph is approximately 100 m on a side.

vey and the industry estimates) are the Diapir Field (15.1 billion barrels), Barrow Arch (4.5 billion barrels), Navarin Basin (3.0 billion barrels), and St. George Basin (1.6 billion barrels), with 2 billion barrels remaining in the rest of the area. The environment in these offshore areas is appreciably different from that encountered in other areas of the world where petroleum exploration and development have taken place. It is these previously unencountered conditions, unique to the polar seas, that constitute the challenge.

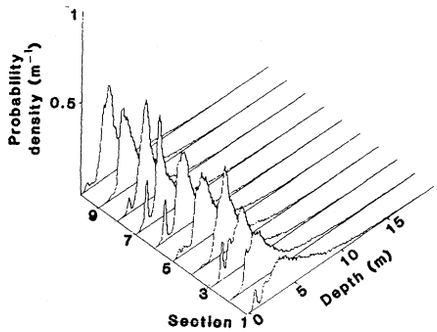


Fig. 4. Probability density functions of ice draft for 50-km sections as determined by the upward-looking sonar on the U.S.S. *Gurnard*; depth increment, 10 cm. The traverse starts north of Kaktovik on the Beaufort coast and proceeds due north for 500 km (*5*).

The Arctic Environment

The areas of most intense interest for offshore petroleum exploration near Alaska are the narrow 100-km-wide and 600-km-long continental shelf of the Beaufort Sea (the Diapir Field) and the much larger shelf of the northern Chukchi Sea (the Barrow Arch). The climate of this region (*3*) is cold and dry and similar to that of the North Slope, an area where industry has demonstrated its ability to operate successfully.

Oceanographic problems in the Alaskan offshore areas are generally less severe than in other areas where offshore development has taken place. Tides and currents are small. More important are surges, which can occur when a major storm approaches or crosses the coast (in October 1983, a storm along the Beaufort coast resulted in a 3-m surge plus 3-m waves, which caused flooding over 1 km inland). Extreme wave heights are believed to range from 30 m in the southern Bering Sea to 15 m in the eastern Beaufort. Certainly wave conditions are generally less severe here than in the Gulf of Alaska or the North Sea in that the fetch at most locations is limited by either the presence of ice or land.

The environmental problems of most concern are invariably those caused by the presence of ice. This is particularly true of areas in the northern Chukchi and Beaufort seas where heavy ice is always a definite possibility, even during the peak of the summer melt. Problems caused by such ice are largely unique to the polar regions and as such are generally outside the base of experience gained in offshore operations in more temperate climates.

Although there are large variations from year to year, the general ice conditions observed off the Alaskan coast may be described as follows. The minimum ice extent occurs during late September and early October. During this time, there is no ice in the Bering Sea and the position of the ice edge in the Beaufort and Chukchi seas, although highly variable, runs roughly east-west. During some years the ice edge is as far as 250 km north of Barrow (Fig. 1). During other years the ice is pressed tight against the coast by onshore winds, blocking the movement of marine traffic. The two most recent "bad" ice years were 1975 and 1983. In 1975 a large barge flotilla bound for Prudhoe Bay was caught in the ice, and in 1983 an even larger flotilla of Soviet ships was trapped off the Chukchi coast of Siberia. Soviet icebreakers, including nuclear-powered ones, had considerable difficulty in freeing the ships (Fig. 2) and at least one ship was sunk. During October the ice edge advances rapidly to the south, moving into the Bering Sea during November. The maximum ice extent occurs during mid-March, with the mean ice edge location reaching almost to 57°N and the extreme ice edge position reaching almost to 55°N (Fig. 1).

Most of this ice is pack ice, which drifts as a result of wind and current forcing. In the Bering and Chukchi seas, fast ice is limited to a few protected bays, the most notable of which is Kotzebue Sound. Along the Beaufort coast there is a more extensive belt of fast ice, whose stability is enhanced by the presence of small barrier islands and grounded pileups of sea ice. As might be expected, pack ice drift rates are highly variable. In the Bering Sea, typical drift rates are 20 to 25 cm/sec, occasionally running as high as 37 cm/sec (32 km/day). The general sense of the motion is southerly toward the ice edge. Particularly high velocities have been observed in the vicinity of the Bering Strait where mean speeds of just under 50 km/day have been calculated. In the Beaufort and Chukchi seas rates of movement are generally lower, with mean annual net drifts varying from 0.4 to 4.8 km/day, while the actual rates (including loops and other irregular motions) reach values as high as 7.4 km/day. In general, drift speeds are lowest during the winter and early spring when the ice is tightly packed and highest during the summer and early fall when the pack opens up. The highest drift rates are invariably observed near the edge of the pack where the ice is moving under nearly free-drift conditions. However, velocities during the winter can be quite high. For example (*4*), during December 1973 floes were observed moving along the Chukchi coast at Barrow at speeds of 8 km/hour over a 5-hour period (associated wind speeds were as high as 90 km/hour). The general sense of the ice circulation is east to west, parallel to the coast and following the general clockwise circulation of the ice in the Beaufort and Chukchi seas. Near the coast, in the fast ice zone, movements are much less, with the total net movement over a winter commonly only a few tens of meters.

The maximum thickness of the undeformed fast ice increases regularly as one moves northward, ranging from roughly 1 m in Bristol Bay in the southern Bering Sea to just over 2 m along the coast of the Arctic Ocean. Pack ice thicknesses are not nearly as well known because there is no simple, rapid method for obtaining this information and direct measurements (drilling) are slow and laborious. In the Beaufort and northern Chukchi seas where ice motions are generally east to west, the maximum fast ice thickness is probably a good index of the maximum thickness of undeformed first-year pack ice. In the Bering Sea where rapid ice movements to the south are the norm, this "conveyor-belt" motion reverses the normal latitudinal variation in ice thickness; as a result, the thickest first-year ice occurs near the southern edge of the pack (1 m appears to be a reasonable estimate of this thickness). In the Beaufort and Chukchi seas, old ice (ice that has passed through at least one summer's melt season) characteristically comprises 25 to 75 percent of the pack. Figure 3 shows an aerial photograph of several thicker floes of old ice embedded in a matrix of first-year ice. The limited sonar profiles of the underside of the old ice suggest a value of 4 m for its modal thickness (*5*), a value in reasonable agreement with thermodynamic estimates (*6*). Figure 4 shows the probability density functions of ice with different drafts for ten 50-km sections as observed by submarine sonar starting in 100 m of water in the Beaufort Sea north of Kaktovik (Barter Island) and proceeding due north. On all the histograms there is an initial peak due to the presence of thin ice in recently refrozen leads and a sec-

ond broader and higher peak at 4 to 5 m due presumably to the presence of large amounts of undeformed old ice.

Even more important is the fact that all the histograms show a pronounced positive skew, indicating that ice even thicker than heavy multiyear floes must be considered, specifically the deformed ice contained in pressure ridges. Ridges are an integral portion of the pack ice environment in that they form by compressive and shearing interactions between ice floes. They can be quite large (Fig. 5), although large ridges are relatively rare. The maximum keel depth and sail height (relative to sea level) that have been observed on free-floating ridges are 50 and 13 m, respectively. The ice over the continental shelf of the Arctic Ocean is more highly deformed (up to ten ridges per kilometer) than ice located farther offshore (two to three ridges per kilometer). Unfortunately, it is this same shelf area that is of prime interest to the oil industry. Few studies have been made of ridging in the Bering Sea, but in general its ice appears to be appreciably less deformed than the ice north of the Bering Strait.

The most impressive ice masses in the Arctic Ocean are the so-called ice islands. These are composed of freshwater "glacial" ice and are fragments of relic ice shelves located along the northern coast of Ellesmere Island, the northernmost island in the Canadian Arctic Archipelago. Ice islands are, in fact, a particular type of tabular iceberg. Typical thicknesses are in the range of several tens of meters. Lateral dimensions are highly variable, ranging between a few tens of meters and 10 km. Although large ice islands are believed to be rare, there is still no adequate census of their numbers and sizes. Two new large ice islands have calved since the spring of 1982, with the largest having dimensions of 9 by 3 km (*7*).

Fig. 5. Large shear ridge along the Chuckchi coast near Barrow, Alaska. The height of the ridge sail is approximately 14 m. The ridge is presumed to be grounded in 20 m of water. [Courtesy of B. Points]

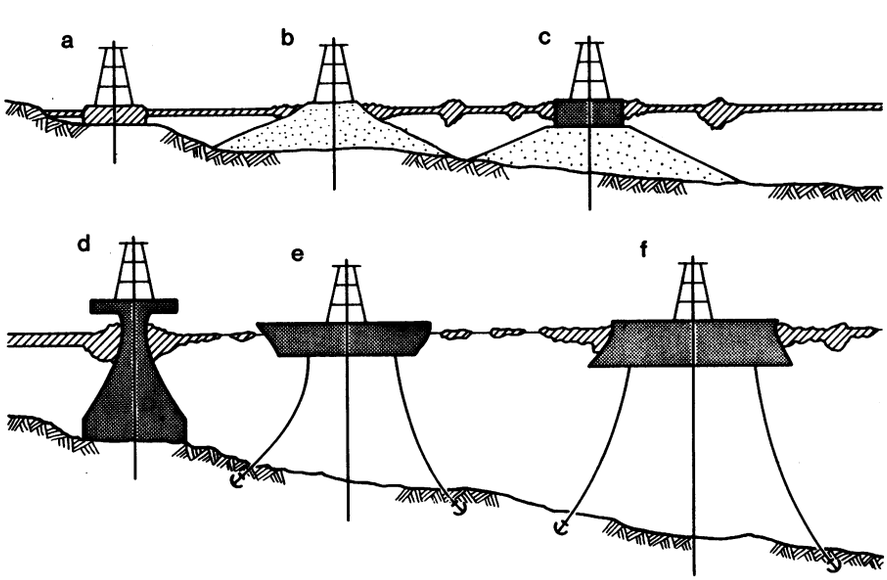


Fig. 6. Schematic of different types of offshore drilling platforms in use (or contemplated for use) in the Arctic: (a) artificially thickened ice pad (winter only), (b) gravel island, (c) gravel berm plus refloatable structure, (d) arctic monopod, (e) drill ship (open water and light ice only), and (f) ice-breaking conical barge. Structure (d) has not been used to date.

Industry Exploration and Production Procedures

The petroleum industry expects to cope with this environment cautiously, at considerable expense, and initially by using approaches developed largely in Canada. Offshore exploration in the Canadian portion of the Beaufort Sea and in the Arctic Archipelago has been under way for 10 years, and a variety of techniques (*8*) for exploratory drilling in ice-infested waters have been pioneered (Fig. 6). In some cases, where the ice-free season is of appreciable length, conventional drill ships have been used during times of no ice or light ice. In addition, ice-breaking tugs have been used to allow drill ships to remain on station well into the winter. At protected sites where ice motions are small, artificially thickened ice platforms have been used successfully (at one shallow site the ice was thickened until it grounded). These techniques are, of course, useful only during exploration because drill ships cannot stay on station over the winter and ice platforms melt during the summer.

By far the most successful and commonly used method of providing a drilling platform has been the construction of artificial islands made with sediment dredged from the nearby sea floor or transported from shore. Initially these islands were constructed at shallow nearshore sites, but they have now been built in water up to 19 m deep at locations far from shore in the moving pack north of the Mackenzie Delta. Because the stable slopes achieved by the fill material are characteristically low, construction of an island of reasonable size in deep water requires an extremely large volume of fill. The time needed to construct such islands may thus be several years, particularly if construction is limited to the ice-free season. The cost is very high. The largest and most exposed island built to date in the U.S. portion of the Beaufort Sea is located in 15 m of water in Harrison Bay, near the fast ice-pack ice boundary, and is referred to as

Mukluk. Its cost is reported to have been $100 million. At some locations in Mackenzie Bay, a gravel berm has been prepared and a steel or concrete refloatable structure placed on top of the berm. To date, the deepest water in which such an approach has been utilized is 30 m.

Although Canadian offshore experience has served as a guide for U.S. offshore operations, this role may reverse in the next few years. The reason for this possible change is that the ice-free season off the U.S. portion of the Beaufort Sea is shorter than north of the Mackenzie Delta (typically 2 months as compared with 3 months). Moreover, ice conditions are generally more severe north of Alaska with more multiyear ice, more ridging, and large ice motions occurring. This increased severity contributes to an increase in construction time, making the cost of gravel islands in deep water very expensive. In general, it is believed that in the U.S. portion of the Beaufort Sea steel and concrete refloatable, bottom-founded structures will become the preferred mode of construction in water deeper than 15 to 20 m. In fact, Global Marine is currently constructing such a structure (*9*) [the Concrete Island Drilling System (CIDS)]. Its first use will be for Exxon, which plans to install it north of Pitt Point (between Mukluk and Barrow) in 15 m of water during the fall of 1984. In deeper waters (20 to 60 m) gravity-based, bottom-founded cone structures appear to be the leading contenders among the several types of structures that are conceptually possible. In the deep waters (up to 200 m) of the Bering Sea, exploratory drilling will undoubtedly take place primarily during the ice-free season. If winter drilling becomes necessary, ice-breaking semisubmersibles are a possible solution.

Once oil or gas is found, exploration systems will be replaced with production systems that are different in three ways: (i) they will be bigger (more work space is required); (ii) they will be designed to last for roughly 20 years; and (iii) auxiliary systems, such as subsea pipelines for transporting the oil, will be required.

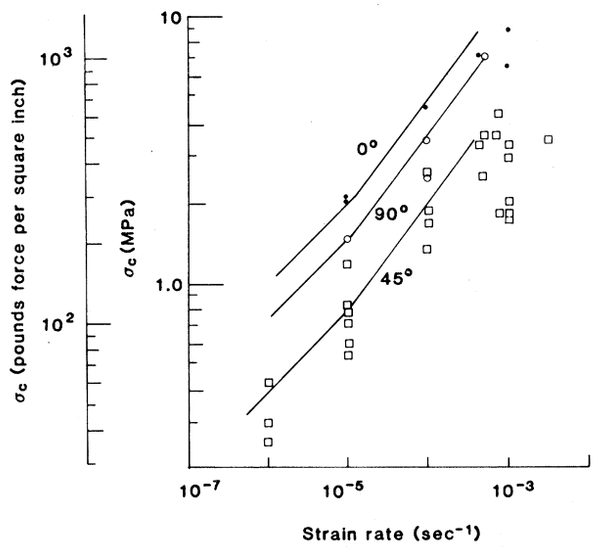


Fig. 7. Variation of the compressive yield strength (σ_c) of columnar first-year sea ice with strain rate and crystal orientation (*16*).

Some Technical Problems

In the offshore Arctic, as in any other area where a major engineering program is contemplated in a new environment, there are many problems arising from inadequate available information. Here we will consider three such problems.

Ice forces. Even pure ice has quite complicated mechanical properties as it invariably exists in nature at near melting temperatures. At high strain rates, it deforms elastically. When strained slowly or subjected to sustained loadings, it is ductile and can creep to large strains without breaking. Sea ice shares these characteristics (*10*). In addition, sea ice contains entrapped salt inclusions, and the amounts of brine, solid salts, and air in the ice are a function of the ice temperature and its salinity (*11*). Salinity in turn varies with the age and thermal history of the ice (after the ice forms it gradually loses salt). There are also several structurally different types of sea ice: (i) congelation ice, consisting of elongated columnar crystals; (ii) frazil ice, which is fine-grained and equigranular; (iii) multiyear ice, which is a layer cake of ice layers formed in successive years; and (iv) "pressure ridge" ice, which consists of irregular fragments of the above ice types that have been refrozen together into a solid mass. It has recently been found that congelation ice can show strong directional *c*-axis alignments of the crystals in the horizontal plane and that the direction of these alignments is controlled by the direction of the current at the ice-seawater interface (*12*). Such ice is structurally ortho tropic in that, at any given level in the ice sheet, the ice properties in the three orthogonal directions are different. There are also major changes in ice properties at different levels in the sheet because of variations in the ice temperature and salinity. These property variations cause the analysis of even simple flexural failures of real sea ice sheets to be far from simple (*13*).

When ice structure interactions are considered, there are several different ways in which the ice can fail (*14*): by bending as it rides up the surface of the structure, by crushing if in-plane stresses reach the crushing load, by buckling if in-plane stresses reach the buckling load, and by splitting. For large structures, failures may occur at different locations and over different spatial domains so that the ice rarely fails uniformly along the complete ice structure contact (*15*). In such a process, more than one type of ice failure may occur simultaneously.

In order to develop realistic estimates of the forces that ice masses will exert on different types of structures, various approaches have been utilized. A large number of small-scale tests have been performed on different ice types under a variety of different test conditions (*10, 16*) in an attempt to develop an ice failure criterion. Some of these results are presented in Fig. 7, which shows the effect of strain rate and crystal orientation on the compressive yield strength of first-year sea ice. As multiyear pressure ridges are considered to be an obstacle that may set design loads on a structure, a variety of studies have been carried out recently on the properties of the heterogeneous ice that comprises such bodies (*17*).

In addition, a variety of scale model tests have been performed (*18*). These tests have been particularly useful in examining the varieties of ice pileup that can occur around structures, the effectiveness of different ice defense mechanisms in preventing ice from overriding structures, and the relative magnitude of ice forces exerted on structures with different geometric configurations.

In an attempt to bridge the gap between the properties of small specimens, the results of model experiments, and the behavior of thick real ice sheets, in situ full ice sheet compression tests have also been performed on about 1.5-m-thick ice. Needless to say, such tests are

very expensive and the number of data points is few; a recent series of full-scale compressive tests performed by Exxon reportedly cost $4 million.

Attempts have also been made to measure the deformations in the gravel fill islands produced by the movement of ice masses. These data have been difficult to interpret as the moving ice invariably fails against the large, complex, grounded ice masses that develop on the island flanks. Therefore, the coupling between the island and the moving ice is not well specified. Although the construction of a steel test structure purely for determining in situ ice forces has been considered, such a program does not appear likely as it would be very costly. The structure would have to be so large that there would be little difference between it and an operational exploration structure. Furthermore, even if a test structure were built, there is no way to guarantee that it would encounter the extremely thick, ridged multiyear ice that would produce ice forces near the design condition. To compensate for this lack, an industry field program is currently under way to determine the stresses and strains in thick old ice floes as they fracture against the sides of Hans Island, a steep-sided rock island located in Kennedy Channel between Ellesmere Island and Greenland. Moreover, the concrete caissons at the caisson-retained island "Tarsiut" (23-m water depth in Mackenzie Bay) are being heavily instrumented, so that stress and strain measurements can be made both on the structure and on the surrounding ice.

At present, there are differences of opinion within the petroleum industry as to the most appropriate way to calculate ice forces. Current approaches include plastic limit analysis (*19*), fracture mechanics (*20*), and the idea of a limiting ice force (*21*). In the use of the last method, it is assumed that the design ice feature is stopped by the structure and that subsequent forces caused by ridge building against the ice feature are transferred directly to the structure. These differences in approach can be additionally compounded by differences in the design ice conditions that are assumed. As "outsiders," we find it difficult to keep track of the state of progress of this subject and of the pros and cons of these different approaches. To the best of our knowledge, there is, as yet, no public set of field measurements that can be used to conclusively test ice force estimates. However, it is doubtful that structures would be designed to resist the forces exerted if a direct collision occurred with a large ice island. Because such collisions are very improbable and because the possibility of such an occurrence would be known well in advance, steps can be taken so that, even if a collision were to occur, there would be no loss of life and no major oil spill.

Gouging of the sea floor by ice. If offshore oil is to be transported south by pipeline, as would presently appear to be the most plausible scenario for offshore discoveries on the Beaufort Shelf, feeder pipelines must be laid between production sites and some convenient landfall. This is a problem because, as the pack ice drifts over the shallower waters of the shelf, the deeper keels of pressure ridges come into contact with the bottom. As the grounding of a few ridges will commonly not stop the movement of the ice, the ice field exerts force on the sides of these grounded features, causing them to scrape and plough their way along the sea floor. Over a period of time, these movements can cause extensive gouging of the sea-floor sediments (*22*). Gouges in excess of 3 m are not rare along the Beaufort Shelf, and gouges in excess of 8 m have been reported off the Mackenzie Delta. Needless to say, this is a phenomenon that clearly must be taken into account in the design of offshore pipelines.

The maximum water depth in which contemporary gouging is believed to occur is roughly 50 m, corresponding to the depth of the largest pressure ridge keels (although gouges occur in water up to 80 m deep, these gouges are presumed to be relics formed during periods when sea level was lower than at present). The distribution of gouge depths in the sea floor is well approximated by a negative exponential with the character of the exponential falloff varying with water depth (*23*). As might be expected, there are fewer deep gouges in shallow water as the large ice masses required to produce such gouges have grounded farther out to sea. For instance, in water 5 m deep a 1-m gouge has an exceedance probability of roughly 10^{-4}; that is, 1 gouge in 10,000 will on the average be expected to have a depth equal to or greater than 1 m. In water 30 m deep, a 3.4-m gouge has the same probability of occurrence.

Gouges are extremely common along the Beaufort and Chukchi coasts, with some regions having in excess of 200 gouges per kilometer. In general, gouges tend to parallel the isobaths. Histograms of the frequency of occurrence of distances between gouges are also well described by a negative exponential; this result suggests that spatial gouge occurrence may be described as a Poisson process. This generalization must, however, be tempered by the fact that there commonly are higher concentrations of gouges on the seaward sides of shoal areas and fewer gouges in the shadow zone on their protected landward sides.

The question is, of course, how deep must one bury a pipeline along a specific route to reduce the chances of the line being hit by a pressure ridge keel to an acceptable value. To answer this problem one must have knowledge of the rates of occurrence of new gouges; these values are very poorly known as they require replicate measurements of the same area of the sea floor so that the new gouges can be counted. At the present time, when one examines the sea floor there is no way to tell whether the observed gouges formed during the last 6 or the last 6000 years. It is currently believed that gouges in shallow water formed over relatively short periods of time. For instance, recent field observations show that hydrodynamic activity during the summer of 1977 obliterated gouges in water less than 13 m deep and caused pronounced infilling of gouges in deeper water (*24*). Such hydrodynamic conditions would appear to have a recurrence interval of roughly 25 years. The length of time represented by the gouges observed at water depths of 25 to 50 m is not well known.

Three attempts have been made to estimate the depth of gouges with specified recurrence intervals. In one case the limited data on observed rates of gouging were used (*23*); in the other two (*25*) information on pressure ridge keels or sails and pack ice drift have been combined to calculate rates of gouging. The resulting estimates of the gouge depths corresponding to different recurrence intervals are quite different. For a pipeline 76 km long, if we assume a water depth of 25 m and the 100-year gouge, gouge depth estimates were 3.1, 4.7, and 7.0 m, respectively. It is clear that these differences should be resolved as soon as possible. Research currently under way includes expanded replicate mapping of the sea floor based on the use of side-scan sonar and precision fathometry, numerical simulations of gouging sequences including the effect of the infilling of gouges with time as the result of the bottom transport of sediment, and tests leading to estimates of maximum possible gouge depths for a given type of sediment.

Oil spill cleanup in areas of pack ice. A problem of a different kind is that of cleaning up an oil spill in an ice-covered sea. The major concern here is an oil well blowout, even though the probabili-

ty of this happening is small. Of the thousands of exploratory wells drilled in offshore waters around the world during the last 25 years, only one—the infamous Mexican Ixtoc blowout in 1979—produced a major oil spill. Far more likely occurrences are smaller spills of various types that can result from routine offshore operations.

The difficulty anticipated in cleaning up an arctic spill is highly dependent upon ice conditions at the spill site (*26*). For instance, if a small spill, as from a subsea pipeline break, were to occur under fast ice, containment and cleanup would be relatively easy because the ice would assist in confining the oil to a relatively small area in that the underside of even flat ice shows an undulating topography [between 60,000 and 200,000 barrels per square kilometer of under-ice surface (*27*)]. Nearshore under-ice currents are generally smaller than 10 cm/sec and currents of about twice this value would be required to move the oil along the underside of even smooth ice. Therefore, the oil will stay in place. One difficulty is in detecting exactly where the oil is located beneath the ice (no simple, reliable remote-sensing technique has been developed as yet). If the oil is not cleaned up by spring, it becomes visible by rising to the ice surface through the increasingly permeable ice. However, by this time the fast ice begins to break up and the opportunity of using it as a stable working "platform" is lost.

If a blowout were to occur in the fall or early winter in a pack ice area, it would be possible to construct a scenario that would allow the well to run unchecked until the following spring. During this period the rising oil from the blowout would cover the underside of the moving ice. If an average drift rate of 2 to 5 km per day is assumed, an irregular strip of oiled ice, about 500 km long and about 150 m wide, would result. Much of this oil would soon be completely encapsulated by the growing ice sheet. Most of the oil released into leads would eventually be incorporated into pressure ridges. We believe that, because of logistic problems and the difficult working environment, clean-up attempts would only have a chance in the spring when, as the result of the rising of trapped oil to the upper ice surface, it would be possible to burn the oil with air-deployable igniters. Burning does not entirely remove the oil. In addition, the logistics of igniting the innumerable oil pools along the 500-km-long oil track are daunting. In all probability, cleanup would not be completed until the ice had melted and open-sea clean-up techniques could be utilized. In some cases this might not occur until years after the actual spill.

In recent years considerable industry and government energy and money have been invested on this problem (*28*). Progress has clearly been made (*29*), but at best cleanup still remains costly and inefficient. We doubt that there will ever be a completely satisfactory response to cleaning up an arctic offshore oil spill other than preventing it from occurring.

Conclusions

After reading the partial listing of unresolved problems and needed research presented here, one might conclude that offshore oil and gas recovery activities in the Arctic should be put on "hold" until all such questions are answered. However, it is clear that this will not happen, nor, in fact, is such a hiatus essential to safe development. Even considering the uncertainties in the problems that have been discussed, enough is currently known to provide the engineer with conservative design values. For instance, if a pipeline were to be buried 8 m, it is clear that the chances of its being damaged by a pressure ridge keel are extremely small (*30*). In fact, such a burial requirement would undoubtedly be excessively conservative. The end result of most of the research that we have discussed would be a more confident and finely tuned answer to the question "How safe is safe enough?"

It should also be noted that we have deliberately avoided discussing a number of contentious issues related to the effect of offshore activities on biological systems, as these matters are outside our area of expertise.

When we began preparing this article, we intended to conclude by advising the reader to watch the results of the drilling on the Mukluk structure in Harrison Bay as a harbinger of future offshore activities in the Alaskan Arctic. However, drilling there has proceeded at a much faster pace than our writing and it is now known that the target beds in the upper part of that structure were filled, not with oil and gas but with water. This makes the Mukluk hole, at an estimated cost of $140 million, perhaps the most expensive single dry hole in the history of the oil industry. Reportedly, the beds had contained oil but the structure leaked (*31*). A disappointment of this magnitude, particularly in view of the fact that it was commonly believed that Mukluk was as close to a certainty as was possible with a wildcat, has instantly thrown a pall over offshore activities. The results will probably be reduced bids on impending Sale 87 (June 1984), which offers 18.0 million acres of the Beaufort Shelf for lease (acreage extends as far as 250 km from shore and to water depths of up to 200 m). To revive interest in the high-stakes game required for exploration in such an environmentally difficult area, a major new discovery will be needed. Locations to watch include Cross Island (Gulf Oil drilling from the outermost of the barrier islands) and Seal Island [Shell Oil drilling from an artificial island (*32*)] and the future (November 1984) drilling north of Pitt Point by Exxon, using the CIDS structure (*33*). Also of considerable interest will be the bidding on the Navarin Basin acreage (March 1984), where the successful companies will have to contend with deep water, high waves, and ice in a location that can well be described as the "middle of nowhere."

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The Open Society

John R. Opel

The American Association for the Advancement of Science represents the finest tradition of American science and engineering. This tradition is based on the premise that science must be open and free, not only providing access for laymen and students to the excitement of scientific discovery, but also inviting them to explore with experts the technological choices open to a free society and to understand their consequences.

Science offers the power to find more choices and better answers, but its benefits must be earned—they are not given. Their price is the willingness to examine critically the future consequences of today's choices, to embrace the inevitability of change enthusiastically, and to trust the processes of our free and open society to guide that change. I applaud and share the optimistic note that I detect in the year 1984.

Thirty-six years ago, in 1948, George Orwell forecast the ultimate chapter in the story of the closed society: mankind's enslavement by a malevolent despot in control of an all-powerful technology. Much of our 1984 world is indeed Orwellian, being characterized by obscurantism, thought control, and forbidden knowledge. But this is not the case in the free world of the West. Here, in the decades since Orwell wrote, we have witnessed not the encroachment of a closed society but a brilliant chapter in a long history of the open society which began in ancient Athens. It is that chapter in which the open society's scientific and technological and industrial progress has blazed the way. Since 1948—through freedom, innovation, and creative energy—the countries of the West, led by the United States, have accomplished a memorable transformation by multiplying our total national output and per capita income many times over and raising up our wartime enemies into giant industrial powers and good friends. We have witnessed an explosion of science and technology increasingly devoted to the human use of human beings.

Indeed it can be said that this year 1984 is not the year of Big Brother and an enslaving closed-circuit television. Instead, it is the year of Everyman, served by a proliferating and liberating new information technology—from the calculator to the copier to the personal computer to new forms of telecommunications.

So in the year 1984 we can, and should, celebrate these triumphs of the open society. But we should also recall, as the people of Athens learned more than 2000 years ago, that those triumphs do not come automatically. The open society, unlike the closed society, has its own particular vulnerabilities, including a propensity to self-indulgence, to contention among special interest groups, and to slackenings in self-discipline. The capacity of the open society to survive and prosper depends—as a closed society does not—on the ability of free individual citizens and their chosen leaders to face facts, think, define, distinguish real problems from false problems, enter into dialogue, and come to agreement.

These are qualities of pragmatism and cooperation. All of us as citizens must use them specifically to reinvigorate three key features of our open society: its economic health and competitiveness; its capacity for self-renewal through its educational system; and its practice of the greatest possible openness in international relations. All three need strengthening and they need it now.

Economic Health and Competitiveness

Let me begin with the reinvigoration of our national economic health and international economic competitiveness. There are many signs of erosion: (i) the drop in our share of world exports from about 18 percent in 1960 to 12 percent in 1982; (ii) a loss of market share here in the United States in such products as steel, automobiles, and consumer electronics; and (iii) a trade balance that has gone from a $9 billion surplus in 1975 to two projected deficits in a row approximating $100 billion each.

We need to undertake many actions to turn these indicators around. The most immediate is to regain our fiscal sanity. In the past 30 years the United States has had exactly four balanced budgets. Our national debt today exceeds $1.5 trillion—nearly $7000 for every American alive. To pay the interest on that debt costs us today 16 percent of our federal revenues. In addition, we face an unprecedented series of future deficits of $200 to $300 billion a year. If these

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