Floating Ice Platforms for Oil Exploration in the Arctic Islands

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ABSTRACT. Exploratory drilling for oil and gas in the Arctic Islands has been in progress since 1961. A majority of the reserves are thought to lie offshore. To drill the offshore structures a method has been developed by which the natural ocean ice is artificially thickened into ice platforms which carry the weight of conventional land drilling rigs. The first ice platform well was drilled in 1974; to date 22 platforms have been built and 13 offshore wells drilled. Ice platform design includes the analysis of stresses in the ice and deflections due to ice creep under long term heavy loads. Deflections are found to be the critical factor with loss of freeboard a possible result.

The arctic environment poses numerous difficulties for construction and drilling operations and logistics are a large part of the effort. Construction of the ice platform is done by flooding the ice with sea water, using submersible electric pumps. During construction and drilling the ice platform is monitored and strains, deflection, strength, temperature, ice movement and other measurements are taken. Special equipment has been developed specifically for ice platform drilling and a subsea completion was made using the ice as a working surface. Further developments of ice platform technology are expected for oil and gas production.

RÉSUMÉ. Dans les iles Arctiques, les forages d'exploration pour l'huile et le gaz se developpent depuis 1961. Le plus grande partie des reserves semble se situer en mer. Pour forer les structures marines, une méthode se developpe avec l'utilisation de la glace naturelle de l'ocean, artificiellement épaissie au droit de plateformes de glace qui supportent le poids des appareils conventionels de forage terrestre. Le premier forage sur plateforme de glace était réalisé en 1974; à ce jour, 22 plateformes ont été construites et 13 forages marins réalisés. Le projet d'une plateforme de glace inclue l'analyse des pressions sur la glace et celle des "fléches" de la glace sous les charges lourdes, pendant une longue durée. Ces fléches sont le facteur critique avec perte possible de l'accastillage.

L'environnement arctique pose de nombreux problèmes pour la construction et les opérations de forage et la logistique demande beaucoup d'efforts. La construction de plateforme de glace se fait en arrosant la glace avec de l'eau de mer, en utilisant des pompes electriques submersibles. Pendant la construction et le forage de la plateforme de glace, on enregistre les tensions, la fléche, la force, la temperature, les mouvements de la glace et bien d'autres mesures on a mis au point un equipement special pour plateforme de glace et completion sousmarine, cela en utilisant la glace comme surface de travail. Des ameliorations supplementaires dans la technologie des platformes de glace sont à attendre pour la production de gaz et huile.

Traduit par Alain de Vendigies, Aquitaine Company of Canada Ltd., Calgary.

INTRODUCTION

Oil exploration in the Canadian Arctic Islands has been in progress for two decades, including exploratory drilling since 1961. The potential hydrocarbon reserves are thought to be very large and the gas discoveries to date have been substantial. All of the major gas fields are known to extend offshore and

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more finds are expected in deeper waters. In the early 1970's the incentive was great to develop a method of drilling offshore which could delineate these petroleum deposits.

The Canadian Arctic Islands with great hydrocarbon potential are at latitudes above 75° N. (Fig. 1). Since thick ice covers the water for most of the year, the offshore drilling vessels and platforms used in more temperate climates could not be used. Instead a method was devised of using the ice itself as the basis for a drilling platform. Floating ice sheets have long been used for temporary roads and bridges and have been used in the Arctic for airstrips and roads for rig moves and seismic surveys. The development of artificially thickened ice platforms to support long-term heavy loads was a natural extension of these techniques; such platforms have proven successful in meeting the requirements of oil exploration and show great promise of aiding the production of the reserves discovered (Watts and Masterson, 1979; Palmer *et al.*, 1979).

The development of offshore drilling platforms was a long step forward in the use of ice as a structural material. Once a decision was made to extend exploration in the Arctic Islands to the offshore regions the techniques developed quite rapidly, starting with the Hecla N-52 delineation well. The evolution of this capability has contributed to the knowledge of ice mechanics and allows further petroleum exploration. Ice platform design and construction is now an established technology and the platforms are reliable structures fitting in well with the natural environment of the Arctic.

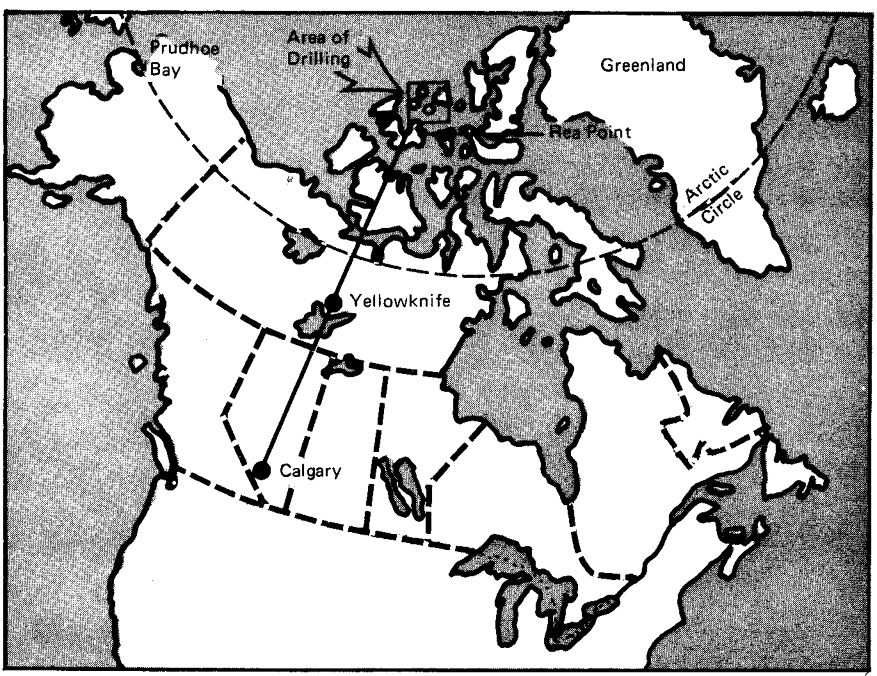

FIG. 1. Ice Platform Drilling Area

THE HISTORY OF ICE PLATFORMS

The first step in the development of ice platform design was the drilling of four stratigraphic test wells in the spring of 1973. These wells were drilled in Kristoffer Bay near Ellef Ringnes Island to depths of 250 - 520 m in water depths of 40 - 90 m. The drilling rig was very small, weighing about 140 tonnes and was supported on natural ocean ice of thickness 2 m.

During these test wells ice strength data was gathered and an ice load test was made using water filled ponds made from snow dikes (Rose *et al.*, 1975). The analysis of these results along with theoretical calculations led to the design of the first Panarctic Oils Ltd. ice platform which was built in the winter of 1973 - 74. The Arctic group of FENCO were the original designers and have been working with Panarctic from early 1973 to date. Comm-Hi Rig #2 was used on this platform to drill the Hecla N-52 well (Baudais *et al.*, 1974). This rig weighs about 450 tonnes; the maximum platform thickness was 5.3 m, consisting of 2.3 m of natural ice and 3.0 m of built-up ice. The designers were on site from the initial location of the site until the rig was removed, monitoring construction of the platform and its performance during drilling. Considerable data and experience from this initial well was used in the design of other platforms.

To date a total of 22 ice platforms have been built by Panarctic Oils Ltd. in the Canadian Arctic Islands and more are planned for the future. Exploratory wells drilled from these platforms now number 13 in addition to the first well drilled from the natural ice (Table 1), including one test production well which was completed or connected to a pipeline flowing onshore. Most of these wells have been near the Sabine Peninsula of Melville Island, with others near Ellef Ringnes Island and further offshore in Hazen Strait, Desbarats Strait and Byam Martin Channel (Fig. 2). The natural tendency is to want to drill wells

TABLE 1. Arctic Ocean Offshore Wells 1973-1979

1.	Panarctic Jackson Bay Strat. B-16*	May	1973
2.	Panarctic West Hecla N-52	April	1974
3.	Panarctic East Drake I-55	April	1975
4.	Panarctic West Hecla P-62	February	1976
5.	Panarctic Jackson Bay G-16A	March	1976
6.	Panarctic Northwest Hecla M-25	April	1976
7.	Panarctic Northeast Drake P-40	March	1977
8.	Panarctic Southwest Hecla C-58	April	1977
9.	Panarctic Roche Point 0-43	April	1978
10.	Panarctic Drake F-76	April	1978
11.	Panarctic Cape Grassey I-34	April	1978
12.	Panarctic Desbarats B-73	March	1979
13.	Phillips Hazen Strait F-54	May	1979
14.	Panarctic Whitefish H-63	May	1979

* Natural ice was thickened for 2 through 8. First monitoring and load testing was done at Site 1.

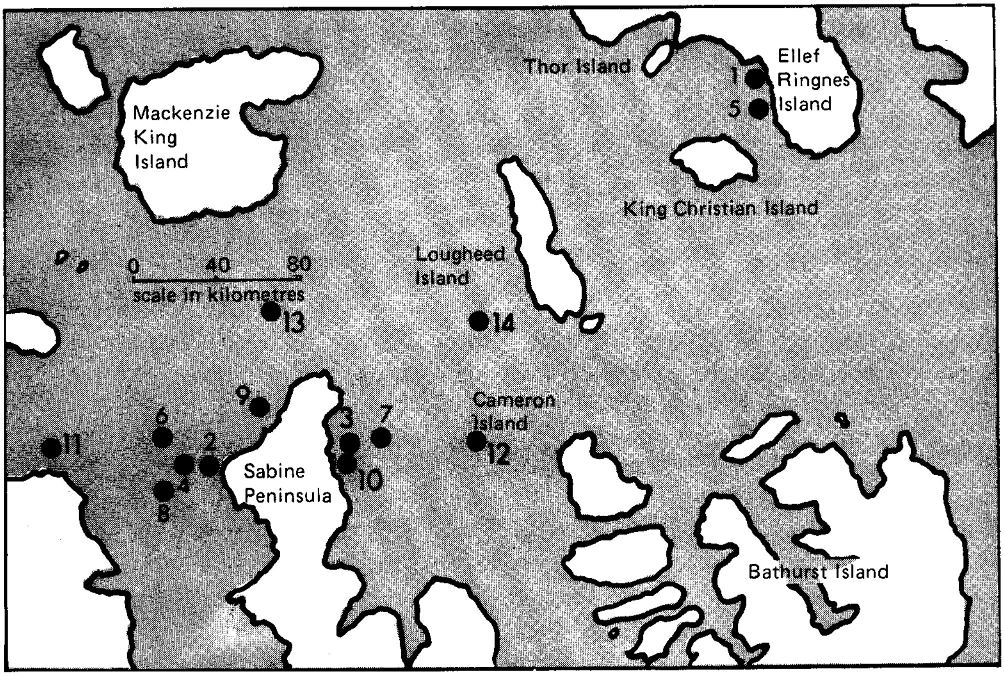

FIG. 2. Arctic Ocean Offshore Wells 1973-1979

to greater depths and move into areas of greater water depths as the search for oil continues. Wells have been drilled from ice platforms to total depths of 3000 m and water depths of 400 m have not caused great problems.

In comparison with other methods used to drill in Arctic waters, such as drillships or manmade islands, ice platform drilling is relatively inexpensive. The rigs used are land drilling rigs, modified to accommodate the movement of the ice. Since the ice platform is floating it moves vertically relative to the ocean bottom with tides. The top of the marine riser which runs to the ocean floor must be supported by hydraulic arms which extend and contract as the tide changes the water level. This movement is much less than that encountered on a drillship, which rolls, pitches and heaves with wave action as well as moving vertically with the tides. Both drillships and ice platforms must also consider horizontal movement, as displacements greater than 5 - 10% of the water depth cause bending of the riser and rotating drill pipe, resulting in large frictional forces, and may force drilling operations to be stopped. While ships rely on large anchors or dynamic positioning systems to maintain position, ice platforms depend on a stable natural ice sheet not moving with the forces of wind or currents. One rig designed specifically for ice platform drilling has the capability of moving the drilling structure 3 m in any direction to compensate for horizontal ice movement. Since allowable movement is determined by water depth, greatest problems may be expected in shallow water. Although ice movement caused a delay in drilling one previous well in shallow water, water depths of 55 m have been drilled successfully.

The major requirement of an ice platform is to support the heavy loads of a drilling rig for long periods of time. The platform must be strong enough not to fail under the weight of the rig, and must float high enough to keep water from flowing onto the working surface of the pad. The strength consideration requires an analysis of the stresses on the platform and has not been a critical feature. The creep or deflection of the platform is usually the limiting factor in the design.

Stress Analysis

Stress analysis of ice platforms uses theory developed for homogeneous, isotropic and elastic plates on elastic foundations. While the assumptions made are not precisely accurate, the results of the analysis have compared favourably with the performance of the platforms. Using formulae developed by Westergaard (1926) and Wyman (1950) the maximum stress developed under a concentrated load can be calculated.

The total rig load is broken down into a series of circular loads from the various parts of the drilling rig (mud tanks, substructure, derrick, engines, etc.). These loads are then superimposed to calculate the largest load and stress at one critical point. The point of highest stress is under the substructure and derrick at the edge of the moonpool — the hole in the platform through which drilling equipment passes.

The material properties of sea ice which are required for the above calculations have been determined experimentally from hundreds of field tests carried out by FENCO personnel. The compressive strength and elastic modulus of the ice are found using a borehole jack specially developed for ice testing. The maximum ice stress calculated with these values is limited to 500 kilo Pascals (kPa) to assure safety of the platform.

The original calculations using the above classical theory did not consider the effects of the taper of the platform nor the moonpool. More recently a Mark CDC finite element computer program has been developed to analyze stresses and deflections in ice platforms (Masterson and Strandberg, 1978). This program takes into account the taper of the platform and the moonpool cutout. The results obtained from the computer analysis have compared very well with the classical solutions and have made possible the analysis of more complicated loads and platform shapes. The analysis has also confirmed that the location of highest stress is under the largest loads by the moonpool rather than at the edge of the platform where the ice is thinner. The additional stress caused by the moonpool is very localized and the maximum increase does not reach more than 40%. This effect may cause some local yielding but does not cause an increase in the deflection of a platform.

Deflection and Creep

The vertical deflections of the ice platform are usually the most critical consideration in the design. Freeboard, or height of the ice surface above the water level, must be maintained to conduct a drilling program. While a slight negative freeboard would not be likely to cause structural failure, the flooding of the working area around the rig would inconvenience and frighten workers and corrective measures would be required. Ice platforms are designed with ample excess freeboard and no problems due to deflections have been encountered.

The instantaneous deflections caused by the stresses in the ice are quite small but the long term deflections due to creep of the ice can be substantial. Elastic plate theory, using an experimentally determined reduced or effective modulus of elasticity, is used to estimate creep deflections. Equations giving the maximum deflection have been derived by Timoshenko (1940) and Wyman (1950). The first experimental tests of these theories used small truck-mounted stratigraphic rigs and a water pond 15 m in diameter (Rose *et al.*, 1975). Since then data from each well have been used to improve the knowledge of ice creep under load.

As soon as the platform is completed the rig is erected and drilling operations commence. The platform immediately begins to deflect down into the water due to creep of the ice; and this creep continues throughout the winter. To evaluate the performance of the platform this deflection of the platform is measured daily. Monitoring the rate of creep is one of the most important activities of the on-site ice specialist and is described further in another section. To date the observed deflections have agreed well with the predicted values. This increases confidence that the theories are accurate and the design is reliable.

As exploration continues in the Arctic Islands the trend is to want to drill deeper wells, requiring heavier rigs. The first stratigraphic wells were drilled from the natural ice using a rig weighing 140 tonnes. The original ice platform well used a rig weighing 450 tonnes and two years later a 720-tonne rig was used. The past two winters the remodelled West-Hi Rig 1, weighing 1350 tonnes, has been used. As rig weights increase a thicker ice pad must be built, requiring a longer construction time. Since deep wells also require a longer drilling period the limiting constraint is the time available to drill in the winter season. This drilling time may be increased by designing light rigs or by speeding up the platform construction. These are considerations for future developments of ice platform drilling.

ICE PLATFORM CONSTRUCTION

The first arrival at an ice platform site can be a new and strange experience for someone not accustomed to arctic regions. After a four-hour jet flight from Edmonton to Rae Point (Panarctic's staging base on Melville Island) and a flight on a Twin Otter to a land base camp near the site, one is well accustomed to seeing a wide expanse of almost featureless snow cover. On the helicopter trip to the construction site it may be difficult to differentiate land from sea, and upon landing there is no indication or feeling of floating over hundreds of feet of ocean. The darkness during the winter months, the low temperature and the rough snow-covered ice makes this a totally new working environment.

This environment is not an easy one for construction or drilling operations. At -40° C exposed flesh freezes quickly and heavy clothes hamper the workmen considerably. Whether trying to do delicate work wearing heavy mittens or having one's eyelashes freeze to a survey level, the efficiency of work is lowered considerably. Some estimates place efficiency under these conditions as low as ¼ that in mild conditions. Experience in Arctic work makes a large difference, however, and the well-planned Arctic operations of the petroleum companies run very smoothly indeed for these severe conditions.

Initial Site Preparation

The first trip to the construction site is made as soon as the ice is thick and stable enough to support the required equipment, usually in late October or early November. A small camp is set up and helicopters bring machines to begin construction of an airstrip and to clear most of the snow off the area where the ice platform is to be built. This is not a simple task as the ice is usually very rough multi-year ice covered with hummocks. The cost of preparing a 1500-m airstrip is usually at least as much as the cost of building the ice platform, even though it is only a fraction of the thickness. The airstrip is very important to the operation: it is needed by Hercules transports bringing the drilling rig and fuel, and by the Twin Otters and Boeing 727 transporting camp and drilling supplies and crews.

Initial flooding of the platform and airstrip to smooth out the surface is done with small, tracked vehicles with drill towers and hydraulic pumps. These

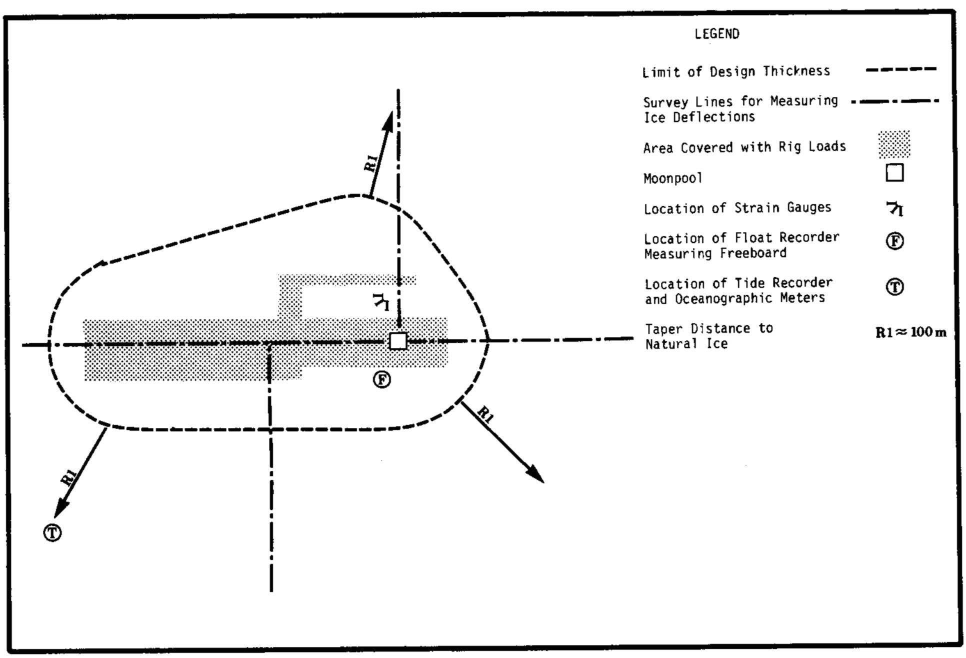

FIG. 3. Ice Platform Layout for Rig 1

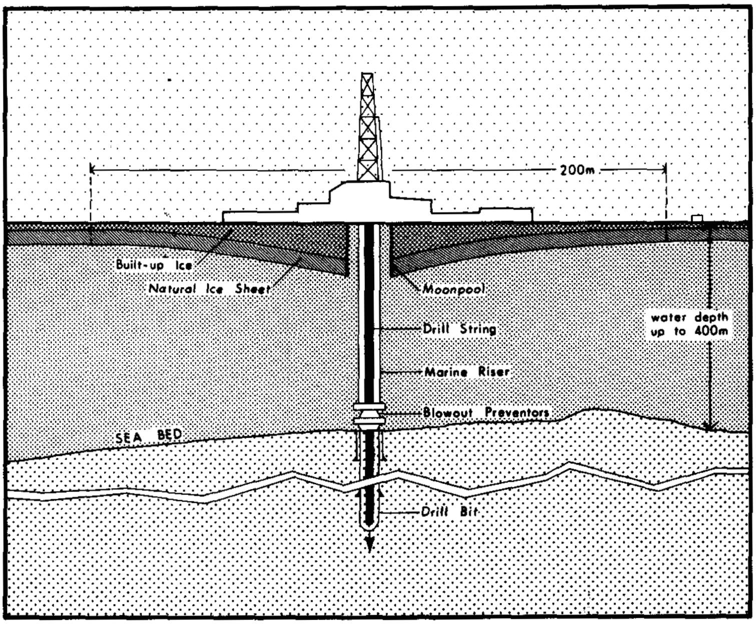

FIG. 4. Section View of Ice Platform Drilling

vehicles drill a hole through the ice, lower a pump into the hole and pump the sea water onto the surface of the ice. The water freezes and fills in the depressions in the rough surface. These small vehicles have proven very successful for this type of operation.

While this initial flooding is taking place the on-site engineers are marking out the platform layout, as shown in Figure 3, and taking the initial profile of the natural ice. At each of the stations shown along the axes and in any low spots the ice thickness is measured. The average thickness is found and the amount of artificially built-up ice required to meet the design thickness is determined. The area encompassed by the broken line in Figure 3 will have this required thickness and the platform will taper off to natural ice thickness at a distance of about 100 m from this line (Fig. 4). The initial thickness of the natural ice affects the time required to build the platform and hence the time available to drill the well. Natural ice thickness may range from less than 1 m for new first-year ice to over 6 m for old multi-year ice. While very thick ice reduces the amount of ice to be built it may cause serious problems due to its extremely rough surface and may be of little net advantage.

Platform Construction

Once the ice is reasonably smooth, usually in late November, two to four electric submersible pumps are encased in insulating wells and frozen into holes drilled in the ice (Fig. 5). These pumps can flood the entire platform with thin layers of sea water, and many frozen layers are used to build the ice platform. While pumping water in very cold conditions is not an easy task, the

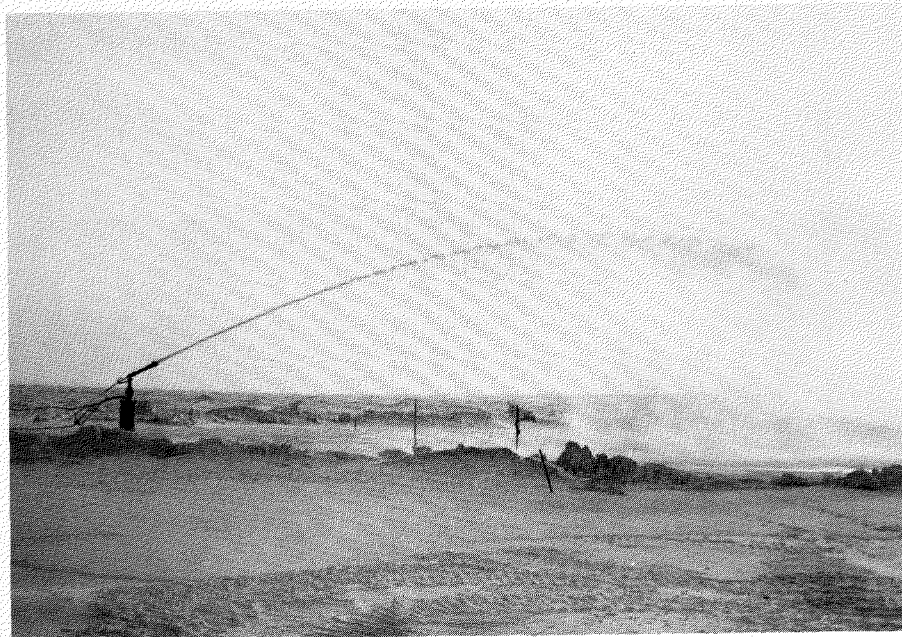

FIG. 5. Submersible Pump With Fire Nozzle

pumps are heated and are very sturdy, and have proven to be reliable in extreme conditions.

Once of the most time-consuming jobs in the construction process is the cutting of the hole in the ice through which the drilling equipment and subsea blowout preventers are lowered. This hole, called the moonpool, is usually cut to within ½ m of the bottom of the ice using chainsaws, jackhammers and other available equipment. The hole is lined with wood timbers to protect the ice sides and the remaining bottom ice is removed after the rig is erected.

The rate at which flooding and ice buildup can proceed is limited by the air temperature. Each flooded layer must be well frozen before the next layer is added. Since thin layers freeze much faster the technique used is to apply several thin layers each day. In very cold conditions the water becomes viscous and freezes very quickly, so the ice specialist is cheered by very cold weather — certainly an unusual outlook. In an attempt to quicken the freezing process nozzles developed for fire fighting have been experimentally adapted to the submersible pumps (Fig. 5). The water sprayed into the air is cooled more rapidly and can also reach longer distances. Unfortunately, other problems are created by the spraying, especially in windy conditions. Average buildup rates have not increased drastically since the first Hecla platform and rates range between 5 and 10 cm/day. The manpower requirements and operational difficulties have been reduced considerably, however, and platform construction is now a well developed and reliable technique.

At a short distance from the wellsite a second ice platform is built at the same time. This platform is designed for another rig elsewhere in the Arctic

Islands. In the remote possibility of a blowout occurring and damaging the drilling rig, the back-up rig would be moved onto this second platform or "relief pad" and would drill a relief well to intersect the blowing well and bring it under control. At present, drilling continues only as long as time would allow a relief well to be drilled, if necessary, before ice conditions deteriorate in the summer.

The main ice engineering problems encountered in building and drilling from ice platforms are not associated with the platform itself. The platform is a thick, stable and well designed structure but its construction and use involves camp facilities and heavy equipment placed on natural ice. The use of floating ice as a bearing surface is not a new procedure and the possible problems are well known (Masterson, 1974). It is easy to forget that one is on floating ice, as there is no sense of floating and no water is visible. Operaters of heavy equipment may park their vehicles in close proximity to the camp, thus depressing the ice around the camp if it is not thick. Holes drilled in the ice or natural cracks could flood the camp if freeboard is not maintained. Natural cracks or leads may cross ice roads over which heavily loaded trucks must drive, necessitating the use of snow bridges or other crossing methods. These and other problems require a careful appraisal of the situation and an application of sound engineering principles. In general, however, the problems faced during ice platform construction are less numerous than those faced in most land-based construction projects.

MONITORING AND TESTING

Monitoring, of both the ice platform performance and ice quality, is an important part of the program. New techniques and equipment have been developed with the aims of increasing the accuracy of measurements and automating the process. Other measurements are also made to increase our knowledge of the environment of the Arctic Islands.

Platform Performance

The most critical performance criterion is the deflection of the platform. Standard surveying techniques, using the surrounding ice sheet as a benchmark, are used to measure vertical deflections. Using a level accurately in the winter darkness and extreme cold is difficult and requires care and patience. Laser levelling using a rotating laser has been tried with reasonable success. Float gauges are very useful to measure the freeboard and give a constant output showing changes as the loads on the platform are changed. Deflection measurements are vital to ensure operational safety and can be used to prevent possible problems. For example, storms can drift large quantities of snow onto the platform, possibly weighing more than the rig. Deflection measurements enable these loads to be detected quickly so the snow can be removed. New techniques to accurately measure deflection will be tried in the future.

The creep, or deflection of the platform under long term loads, is measured to test the validity of the design calculations and to provide a direct indication of the safety of the platform. Three types of creep may be experienced with a loaded structural member. Primary creep is encountered immediately after loading and is indicated by a decreasing rate of deflection. Secondary and tertiary creep are evidenced by constant and increasing deflection rates respectively. For the time periods under consideration primary and secondary creep are considered safe; tertiary creep indicates that failure is imminent. To date primary and secondary creep have been noted but tertiary creep has not occurred. The distinction between primary and secondary creep may not be obvious as the loads on the platform are constantly changing due to varying snow loads, hook loads, supplies and pipe weights. The analysis of changing creep rates has provided good verification of the design and has increased our confidence in the safety of ice platform drilling.

Strains in the ice have been measured using specially built strain gauges developed for ice platforms (Masterson *et al.*, 1979). Constantan wires with length of 3 m and diameter of .127 mm are anchored at each end and flooded into the ice during construction. Three gauges, each consisting of two such wires, are placed in rosette fashion at five vertical levels through the platform. The change in resistance of the wires as they stretch or contract provides a value of the strain in the ice in tension or compression, respectively. A loaded plate such as an ice platform experiences maximum compression near the top, maximum tension near the bottom and very little strain near the centre. Strain profiles through the platform under a heavy rig load have been obtained using the two wires in each gauge as a check. The results are likely to have significant effects on the theories used to predict the behaviour of ice in flexure and on the future development of ice platform construction.

Ice temperatures are measured as vertical profiles at several locations on the platform using strings of pre-wired thermistors. Flooding rates are controlled to keep the average temperature of the platform below -5° C. The effects of the relatively warm water in the moonpool can be monitored during drilling and the thoroughness of the freezing process can be ensured during construction.

Ice strength tests are made throughout the ice depth using a FENCO borehole jack developed specifically for the purpose (Kivisild, 1975). These tests can also be used to obtain the elastic modulus of the ice. Weak or slushy ice can be detected and adjustments can be made to the design where necessary.

The confirmed compressive strength measured by a borehole jack test for natural sea ice may range from 14 to 34 Mega Pascals (MPa). Ice built up by flooding has strengths within this range except for a thin layer about ½ m thick near the interface between natural and built-up ice. Brine trapped in the built-up ice during flooding migrates downwards and accumulates here, lowering ice strengths to as low as 6 MPa. This ice has proved more than adequate to transfer shear stresses and poses no constraints on the design.

Other Measurements

Data collection programs in addition to those required to monitor platform performance have been carried out at the drilling sites. Two of these measurements are essential to the drilling program: horizontal ice movement and vertical ice movement.

Horizontal ice movement is caused by wind and current forces on the ice pack and has been measured in various ways. The first method developed involved measuring the distance from two nearby onshore stations with conventional tellurometers. A backup system measured the angle of a guideline wire which was connected to the ocean floor. This system included an alarm which sounded when the movement reached 5% of depth (the angle at which drilling operations could be hampered). A new system to measure ice movement farther offshore uses signals broadcast from orbiting satellites to calculate position fixes. The measurements taken at 13 well sites indicate that horizontal ice movement is not a great obstacle to drilling in the stable pack ice of the Sverdrup Basin. Nevertheless this movement is the major limitation in the use of ice platforms in other Arctic areas. In the Canadian Beaufort Sea and in the Eastern Arctic most areas have ice movement which prohibits the use of ice platforms for oil exploration.

The vertical ice movement is caused by the tidal change in water level. Although the tidal range in the Arctic Islands is often less than 1 m, it has a considerable effect on drilling operations. The bottom of the marine riser is fastened solidly to the sea floor and the top is connected to the drilling rig via hydraulic arms which compensate for vertical motion. When the riser is installed the position on the tidal cycle must be known, hence tidal movements are measured constantly throughout the construction and drilling programs.

Other oceanographic measurements are taken to improve our knowledge of the arctic environment rather than specifically for the drilling program; these include ocean currents and salinity and temperature profiles. Each site also keeps a complete log of weather observations. The various data collection programs financed by the petroleum companies are of great use in extending our knowledge of ice mechanics and the environmental sciences as applied to the Canadian Arctic.

ICE PLATFORM DRILLING SYSTEMS

Ice platform drilling is significantly different from other offshore exploratory drilling systems in that conventional land rigs can be used. This means that platform-based wells can be drilled for much lower costs than those using other systems, due to the very high costs of drillships, artificial islands or offshore structures. Baudais *et al.* (1974) estimated that the first ice platform well cost was ¼ that of other systems. Today the difference may be even greater.

The main differences between land drilling and ice platform drilling systems are the marine riser and other subsea equipment and the blowout prevention system. In addition to the blowout prevention system normally used by the rig on land, a second set of blowout preventors is set at the ocean floor. Due to the relatively small size of the rig, the limited capacity of the ice platform and the necessity for aircraft transportation, the subsea equipment must be as light and compact as possible. The equipment must also be hardy to withstand the arctic environment. The subsea system is placed without the use of divers and is designed to enable both manual and automatic closure of the well in the event of sudden large ice movement or other emergency which might prevent well control from the surface. It incorporates testing systems and emergency and backup methods of closing the well. The marine riser can be quickly disconnected from the subsea stack without diver assistance and in such a case the well could be re-entered. The exploratory well is abandoned with no obstructions left above the ocean floor.

A new drilling rig, the West-Hi Rig 1 (Fig. 6), has been designed specifically for drilling from ice platforms. Although it is heavier than would be ideal it incorporates some highly desirable features. The design provides for a wide distribution of loads on the ice (Fig. 4). This reduces the thickness of ice required and also leaves enough room for the substructure to be skidded in any direction to compensate for limited horizontal ice movements (Watts *et al.*, 1979). This rig, like all ice platform rigs, can be broken down into loads which fit the Hercules aircraft. It is designed to drill deep wells from ice platforms in the winter and also to drill from land in the summer.

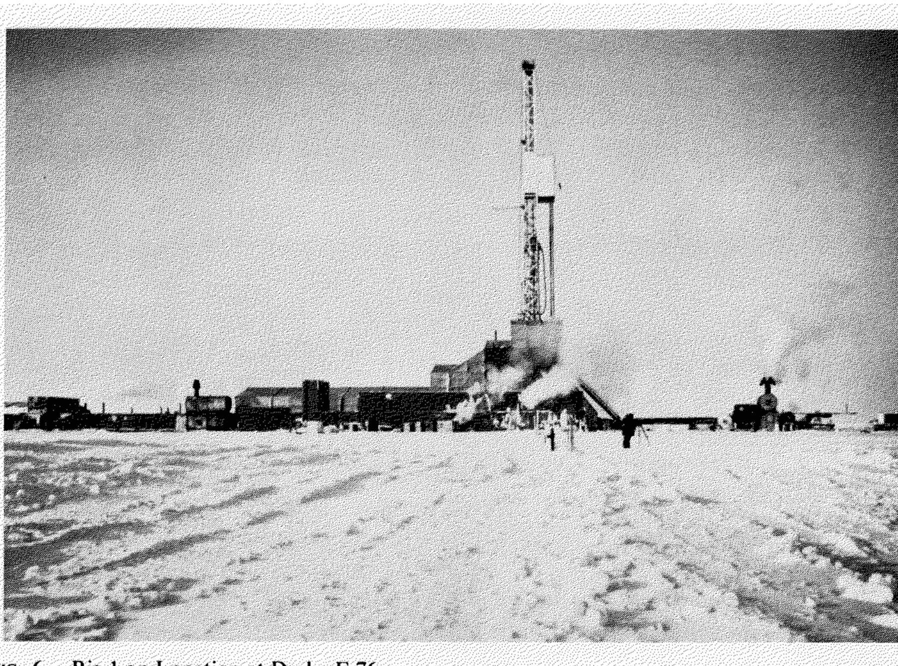

FIG. 6. Rig 1 on Location at Drake F-76

The most severe constraint on ice platform drilling programs is the limited time in which drilling may take place. The start of drilling must wait for the ice platform to be completed, which in turn is limited by the time at which stable ice conditions occur in the late fall. Drilling continues only as long as time remains to drill a relief well before the ice starts to melt or break-up. This means that drilling is done in only half the available time after the platform is completed. Future changes to ice platform techniques will likely place emphasis on methods to increase the time available to drill exploratory wells.

SUBSEA COMPLETIONS

As exploratory drilling reveals large deposits of gas in the Arctic Islands the obvious need is for a method of bringing this gas to a pipeline or shipping facility. This involves completing the well: connecting it to a pipeline flowing onshore. In April 1978 the world's first Arctic subsea completion was made at Panarctic's Drake F-76 well (Palmer *et al.*, 1979). While this was a test completion less than 1 km from shore in water only 55 m deep, it demonstrated techniques which could be used to develop gas reserves 35 km offshore in water 500 m deep. The pipeline was laid and connected from the ice surface and was designed to be installed without the requirement for divers (Hood *et al.*, 1979).

The main danger facing a subsea pipeline in the Arctic is the possibility of ice scour. This can be avoided by burying the pipe in all areas where scour may occur. The offshore parts of the F-76 flowline were buried in a trench 1.5 m deep, although some pipelines will require burying considerably deeper. The soil around the pipe was refrigerated to form a protective cylinder of artificial permafrost. For protection near the shore crossing an ice berm was built to protect the pipeline. Built by standard ice platform construction techniques, the berm was grounded and covered with an insulating layer of gravel. The permafrost boundary is expected to migrate further offshore over the years. The berm and pipeline are still being monitored and the data collected will be used in future designs.

The Drake project has demonstrated the feasibility of completing and producing offshore wells in the Arctic Islands from floating ice platforms with a modified land rig, and pulling a pipeline into position from the ice surface. The use of ice as a working platform has proven to be an important part of the production of hydrocarbons in the Arctic Islands.

SUMMARY

Exploratory offshore drilling in the Canadian Arctic Islands from floating ice platforms has proven very successful. Wells have been drilled in water depths of 55 - 400 m and to total depths of 3000 m.

Designs based on elastic plate theory have been used since the first platform was built in 1974. Finite element computer analysis and platform monitoring programs have verified the conclusions of the theory and allowed more detailed and accurate designs to be made and relied upon. The most critical design consideration is usually the long-term creep or deflection of the platform. To date 22 ice platforms have been built and 13 exploratory wells have been drilled with highly favourable results.

Construction and field monitoring procedures have developed considerably since the first platform. In the severe environment of the Arctic Islands thorough planning is a necessity. Flooding is now largely automated, and provision of logistic support facilities (such as an airstrip) takes up a majority of the construction effort and cost. Submersible pumps are used to flood the platform and build the ice. Buildup rates range from 5 to 10 cm/day, depending on air temperature. Three different techniques are used to measure the deflection of the platform caused by the creep of the ice. The strain in the ice is measured throughout the ice thickness and the values obtained are used in future designs. Temperatures, ice strength, vertical and horizontal ice movement and oceanographic measurements are also taken to monitor the platform and surrounding environment.

Conventional land rigs are used with some modifications. Sophisticated blowout prevention and subsea equipment is required to ensure safety and flexibility. One well has been successfully completed to a pipeline flowing onshore and production tested. The future for gas production in the Arctic Islands looks optimistic; large reserves have been proven and a method of production has been developed. More exploration will be done and a pilot project may soon produce gas and transport it to markets. Ice platforms will play a role in these efforts, and testing and development will continue in the future.

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REFERENCES

BAUDAIS, D.J., MASTERSON, D.M., and WATTS, J.S. 1974. A system for offshore drilling in the Arctic Islands. 25th Annual Technical Meeting of the Petroleum Society of CIM, Calgary. Paper No. 374029.

HOOD, G.L., MASTERSON, D.M., and WATTS, J.S. 1979. Installation of a subsea completion in the Canadian Arctic Islands. 30th Annual Technical Meeting of the Petroleum Society of CIM, Banff. Paper No. 79-30-20.

KIVISILD, H.R. 1975. Ice mechanics. Third International Conference on Port and Ocean Engineering Under Arctic Conditions, University of Alaska, Fairbanks.

MASTERSON, D.M. 1974. Floating ice sheets. The Northern Engineer 6(3). 11-18.

——— and STRANDBERG, A.G. 1978. Long-term loading analysis of floating ice platforms using finite element technique. N.R.C. Workshop on the Bearing Capacity of Ice, Winnipeg.

———, ANDERSON, K.G. and STRANDBERG, A.G. 1979. Strain measurements in floating ice platforms and their application to platform design. Canadian Journal of Civil Engineering. 6(3): 394-405.

PALMER, A.C., BAUDAIS, D.J., and MASTERSON, D.M. 1979. Design and installation of an offshore flowline for the Canadian Arctic Islands. Offshore Technology Conference, Houston. Paper No. 3446.

ROSE, G.D., MASTERSON, D.M., and FRIESEN, C.E. 1975. Some measurements of laterally-loaded ice sheets. IAHR Third International Symposium on Ice Problems, Hanover.

TIMOSHENKO, S. 1940. Theory of plates and shells. McGraw-Hill. 580pp.

WATTS, J.S. and MASTERSON, D.M. 1979. Completion of an offshore well in the Canadian Arctic Islands. Offshore Technology Conference, Houston. Paper No. 3445.

WESTERGAARD, H.M. 1926. Stresses in concrete pavements computed by theoretical analysis. Public Roads. V.7.

WYMAN, M. 1950. Deflections of an infinite plate. Canadian Journal of Research A28: 293-302.