SECOND INTERNATIONAL CONFERENCE ON
PORT AND OCEAN ENGINEERING UNDER ARCTIC CONDITIONS
UNIVERSITY OF ICELAND
DEPARTMENT OF ENGINEERING AND SCIENCE

THE MOVEMENT OF ARCTIC LANDFAST ICE: ITS MEASUREMENT AND INFLUENCE ON OFFSHORE DRILLING

K.R. Croasdale Imperial Oil Limited Calgary
Engineer Canada

INTRODUCTION

The high demand for oil and gas is gradually depleting traditional areas of supply, particularly in North America. It is for this reason, that, despite the difficulties posed by the harsh environment, the offshore areas of the Arctic are receiving the attention of oil and gas producers. Almost all of the Canadian Arctic offshore out to the edge of the continental shelf is under permit to oil companies. The issuing of oil and gas exploration permits by the government carries with it an obligation to perform exploration work to a certain expenditure level. Meeting the expenditure obligation usually requires exploration drilling well before the twelve to fifteen year term of the permits is up.

The area of the Canadian Arctic prospective for oil and gas covers about 300 million acres and about half of this lies offshore. It is obvious, even to the casual observer, that the Arctic offshore environment is an extremely difficult one in which to operate. As every school boy knows, the Arctic waters are covered by ice for most of the year and it is this ice which makes the area so different in terms of oil and gas producing operations. Even in the most southerly part of the Canadian Arctic, the sea is covered by ice for about nine months of the year. In the more northerly areas, the ice never clears but just becomes more mobile.

It is beyond the scope of this paper to discuss in detail the effects of the presence of ice on offshore oil and gas operations; however, some brief comments are appropriate.

Following (or before) the issuing of permits for oil exploration, the first task of the operator is to define geological structures having the potential to be productive. The main element of this phase of exploration is seismic investigation. Offshore, this is done from a vessel trailing a long cable containing sensitive geophones. This operation can also be performed from stationary ice sheets but this is more time consuming. Much seismic work in the Arctic offshore areas has already been done during the brief open water periods in the summer.

The next phase of exploration is "wildcat drilling in which potentially attractive geological structures are tested for the presence of hydrocarbons. During this operation, a stationary platform is required from which to drill. Depending on the depth of the hole, the drilling will take between about 30 and 100 days. In conventional offshore areas, wildcat drilling is done from either a moored vessel or some kind of temporary bottom-founded structure; the best choice being a function of water depth, maximum wave height, seabed conditions, etc.

If wildcat drilling is successful, additional drilling will be done to assess the reservoir. If it is commercial, production wells will be drilled and produced either from bottom-founded platforms, or in deeper water, via sub-sea production systems now under development.

From the above it will be seen that the drilling operation is a vital element in the cycle of oil and gas production. It is the technology to drill offshore in the Arctic which is currently receiving the attention of oil industry engineers, and which has stimulated the work described in this paper.

ARCTIC OFFSHORE DRILLING

To date, no deep exploratory holes have been drilled offshore in the Arctic. Recently, however, Panarctic drilled four 1000 foot deep exploratory holes for geologic information, just offshore from Ellef Ringness Island in 150'-300' of water. A light-weight rig was used working off the ice. Light-weight coring rigs have also been used on the ice in the South Beaufort Sea to sample the seabed for foundation design. Such sampling seldom requires seabed penetration greater than 100 feet and can usually be accomplished in one or two days. As I deliver this paper, my company will be assembling a drilling rig on Immerk B48, a dredged island, in ten feet of water in the Mackenzie Delta area of the Beaufort Sea. This will be the first wildcat drilling operation to be performed offshore in the Arctic.

Many schemes have been proposed for drilling offshore in the Arctic and are well publicised[1]. There are basically three possible methods, namely:

1. Summer drilling from a conventional floating vessel during the open water period.
2. Drilling from a bottom-founded structure or island.
3. Drilling from the ice.

Obviously, the first method is only viable if a sufficient open water period exists to drill a hole to sufficient depth. The second method becomes increasingly difficult as the water depth increases, and beyond the 200 foot water depth the structural difficulties become extreme. The third method requires that the ice be stationary (or essentially so) or a technique is required to move the rig in order to stay over the original point of entry into the seabed.

EFFECT OF ICE MOVEMENT

The amount of ice movement affects the design of both bottom-founded and off-the-ice systems. Many different shapes of structures have been proposed for use in ice-infested waters[2]. The biggest problem in designing such structures is to provide an ability to resist the high lateral forces imposed by the moving ice. Typically, lateral forces due to ice will be an order of magnitude greater than the worst wave forces for which similar structures might be designed in conventional offshore areas.

The lateral ice force will be a function of the ice strength appropriate to the relevant mode of failure of the ice. For vertical sided structures, the crushing strength will govern, while the bending strength will be relevant to forces on a sloping structure.

At low rates of loading, ice behaves in a visco-elastic fashion. Therefore, at very low rates of movement, an ice sheet might be expected to "flow" around a structure without exerting the worst load. Several years ago, it was believed that structures which would be surrounded by landfast ice might not need to be designed for the worst possible ice pressure. However, better knowledge about ice properties and rates of movement of landfast ice suggest that such a mitigation is not possible and structures placed in landfast ice areas will need to be designed for the worst lateral ice forces.

Some types of structures in shallow water might be designed to absorb a limited amount of ice movement. As an example, consider a dredged island which might have typical beach slopes of 1 in 20 or 1 in 10. Motion of the sheet ice around the island could conceivably lead to ice pile-up or ice ride-up on the beaches. For an island with a typical diameter above water level of say 500 feet, an ice movement of about 50 feet will be no great problem; however, if a thick ice sheet moved several hundred feet, the ice might move right over the island surface and cause much damage.

Ideally, off-the-ice drilling requires the ice to be essentially stationary. I say "essentially" because, as in conventional floating drilling, some horizontal motion is permissible. If a conventional well head and riser is used, about a five degree inclination can be tolerated. The allowable ice movement is then a function of water depth; typically, in 100 feet of water, 10 feet of lateral ice motion could be accommodated.

Another problem associated with off-the-ice drilling is that of supporting and transporting the rig and equipment which will weigh several thousand tons. A novel solution to this and the ice movement problem has been proposed by Arctic Engineers and Constructors. Their solution, illustrated in Figure 1, is to mount the rig on a barge which floats in a melted hole in the ice. Ice movement is counteracted by an ice melt system around the barge perimeter and a positioning system consisting of winches, cables and ice anchors. The total system can be air-cushion supported for moving across the ice onto location. Obviously, the viability and unit costs of such a system are very sensitive to the maximum rate and total amount of ice movement in the areas of interest.

TYPES OF ICE MOTION

Attempts to categorise ice according to its motion characteristics have led to a rich and varied terminology. Roots[3] has suggested that sea ice be categorised (according to its motion) with the following terms.

"(a) Pack ice: floating ice whose translation under wind and current is such as to enable it to move bodily into or out of the area under consideration over periods of days.

(b) Near-shore constrained ice: ice that moves freely in a vertical direction with the tides and normal changes of sea level, and which may not be physically fastened to the land, but whose bodily lateral movement is rarely more than a few meters over periods of days in normal weather.

(c) Stationary ice: ice in which the movement in any direction is negligible (less than a metre) over periods of days in normal weather."

The last two types are those normally defined as "fast ice" which is sometimes prefixed as landfast or shorefast ice. The Pilot of Arctic Canada uses the term "fast ice" but on its maps refers to such ice as "solid and unmoving". These maps show that in winter, fast ice covers all of the Canadian Arctic Archipelago, except Lancaster Sound and Prince Regent Inlet and extends out from the Beaufort Sea coast to a distance of up to 30 miles (see Figure 2). The total area covered by fast ice in the winter makes up about 50% of the potential oil and gas bearing offshore area referred to earlier. Therefore, an understanding of the formation and motion characteristics of fast ice is obviously of some importance and particularly in terms of selection of the best system for offshore drilling.

THE FORMATION AND EXTENT OF FAST ICE

In the South Beaufort Sea freeze-up averages about the second week in October and by spring a belt of fast ice extends out to about the ten fathom line. Earlier in the winter, the extent of the fast ice is a function of the ice thickness and wind conditions. During November and December the fast ice is often limited to about the two fathom line. Mobility of the ice during this period in the area bounded by the two and six fathom lines accounts for the extensive ridging which can occur in the area, even though it appears to be landfast by the end of January.

Under the action of southerly winds, the mobile pack ice moves away from the fast ice and an open lead forms along its edge. As shown in the excellent satellite photograph, Figure 3, the lead can open up to 5 to 10 miles in width. It will close again when winds change back to northerly.

The satellite photograph also gives an excellent illustration of how the fast ice edge uncannily follows the ten fathom depth contour, even in an enclosed area like Mackenzie Bay where we might have expected some bridging across the deeper water. The only explanation seems to be that in the Beaufort Sea the existence of the fast ice is a function of the presence of grounded ice features. It perhaps further implies that grounded ice features are currently not common in water deeper than about 10 fathoms.

It is puzzling to note that even with the help of grounded ice features, the fast ice in the South Beaufort Sea does not extend out from shore more than about 30 miles. Whereas in the Arctic Archipelago, straits and channels over 100 miles wide are covered by fast ice which is not that much thicker.

Presumably, the forces imposed on the Beaufort Sea fast ice by the Polar ice of the Arctic Ocean are large enough to cause its disintegration except when protected by grounded ice or land features. There is an obvious analogy with the wave height and fetch relationship. The "wind stress fetch" affecting the coastal ice of the South Beaufort Sea is a thousand miles or so, whereas in the Arctic Archipelago, "fetches" between land points are generally less than 100 miles.

TYPICAL MOVEMENTS AND PREVIOUS MEASUREMENTS

To the casual observer fast ice appears solid and motionless and this is a valid observation when compared with pack ice, which can move several miles per day. However, as a continuous sheet of deformable material subject to wind stress and pressure from adjacent pack ice, small movements of land fast ice are to be expected. Further, temperature changes might also be expected to cause expansion or contraction of the ice sheet.

In fact, it is now well known that movements of several metres can occur. In the winter of 1968-69, Dr. P.F. Cooper[4] used survey stakes in Kugmallit Bay and measured ice movements of up to six metres during the period January 20 to March 20. As a result of these measurements, Roots[3] suggested that due to temperature changes alone, movements of 60 centimetres per kilometre might occur. Over a 30 mile length this gives a movement of about 100 feet. It is of course of some interest to know if such a movement can occur in a matter of minutes or hours or whether it takes days or weeks.

TECHNIQUES FOR MEASURING MOTION OF FAST ICE

Referencing to Shore

Survey techniques referencing to the shore are an obvious method and were used by Cooper[4]. Unfortunately, if successive survey steps have to be made from shore to reach the more distant sites, cumulative error can be greater than typical motions, and such a technique is to be avoided.

To be useful, direct survey techniques from shore to ice stations will require intense light sources or else the use of microwaves. In addition, high points on the shore are needed to get the range required. (That is unless the technique described below is used.)

In the spring of 1970, Imperial Oil Limited operated, on behalf of the Canadian Arctic Petroleum Operators Association, an ice measurement programme in the South Beaufort Sea. Part of the programme was a series of surveys to measure ice movement. Fifteen locations on the land fast ice between Herschel Island and Cape Bathurst were surveyed. Each site was surveyed two or three times during the period March 6 to May 16. The sites were located using a microwave positioning system. This consisted of two portable responders and horn antennas which could be placed at selected shore sites, and a two-range interrogator and omnidirectional antenna mounted on a helicopter (see Figure 4). When a site was ready to be surveyed, the responders with batteries were located at geodetic control stations on the shore. The antennas were aimed in the direction of the site to be surveyed or re-surveyed. At the site a laser beam was placed on a tripod so that it pointed vertically upwards. The helicopter then hovered above the laser and with the aid of a closed circuit T.V. monitor, intersected the laser beam. The intersection activated the interrogator and the distances to the shore stations were automatically printed. Use of the laser beam and the helicopter eliminated the need for tall antenna masts on the shore, and sites as far as 30 miles offshore were surveyed with an accuracy of $\pm$ 5 feet. Repeated surveys enabled ice movement to be assessed but usually, because of logistical problems, the period between surveys was one or two weeks.

Other survey techniques have been proposed but they all suffer from similar drawbacks, namely: a) logistics problems (especially during the dark months of November, December and January) and b) a coarse time scale between surveys which does not give satisfactory indications of ice movement rates.

Referencing to Seabed

An inclinometer used in conjunction with a taut wire between ice and seabed (see Figure 5) was an arrangement developed to measure ice movement, by Oceanographic Services in 1969. Three of these devices were used in the previously mentioned Beaufort Sea ice survey in 1970. This system has the advantage of simplicity and can record ice movement continuously (although recorder capacity usually limits the recording period to 1 or 2 hours per day). Because of the problem of maintaining a taut wire, the device is not recommended for water much deeper than about 100 feet. At this water depth, the range would be 100 feet for a typical 45° inclinometer. An accuracy of 1-2% of water depth is claimed.

The water depth and range limitations of the previous device led to the development by the same company of a multipath acoustic ranging system (see Figure 6). The main elements of the system are a bottom-mounted reference transponder and an array of hydrophones suspended just below the ice. The data is recorded automatically on magnetic tape at pre-selected time intervals. The water depth range is 50 to 1000 feet. The maximum horizontal range is about three times the water depth (up to 2500 feet slant distance). An accuracy of 0.5% of the water depth is claimed. I personally have had no experience with this system but it has been used successfully by others both in the Beaufort Sea and the Arctic Islands.

THE WIRE/REEL SYSTEM

Requirements

The previously mentioned devices all have certain merits but also some disadvantages, and are costly; particularly if near-continuous readings of movement are required at numerous sites. For this reason, we began a search two years ago for a system better suited to our needs.

Our initial requirement was for a simple mechanical device which would measure ice movement relative to the seabed. It had to be simple, reliable and cheap enough to enable numerous locations to be surveyed. We also desired that it could be read manually by visiting the site, or else remotely by recorder or telemetry system. Our immediate area of interest was the land fast ice extending northwards from Richards Island in the Mackenzie Delta area of the Beaufort Sea (see Figure 9).

Development of the Equipment

The equipment as originally developed, and which has since remained virtually unchanged, is shown in Figure 7. The spring loaded reel (Figure 12) contains 100-300 feet of fibreglass tape connected to an anchor via a plastic tube set through the ice. At the bottom of the plastic tube, which is 3 inches in diameter, is an aluminum or P.V.C. ring to help reduce friction and wear on the tape. The maximum length of tube is 15 feet but, in shallow water, the tube length is shortened so that the bottom of the tube is about 2 feet above the seabed. The tubes are filled with gelled diesel fuel to discourage freezing at the water interface. The use of a plastic tube (rather than metal) and an insulated cover are also features designed to minimize freezing problems.

At telemetered stations, a 40-turn rotational potentiometer (1000 ohm) is mounted on the reel shaft. The voltage response of the circuit is then a direct analogue of the amount of tape pulled off the reel. At most sites, two measuring devices were installed either to ensure redundancy or to enable direction to be estimated by orthogonally offsetting the anchors. At some sites, however, a direction arm was installed, as shown in Figure 8. The direction arm is connected by a flexible drive to another rotational potentiometer so that a direct analogue signal of direction can be obtained.

The Telemetry System

In the first winter of operation, we installed telemetry equipment at just five of the ten ice movement sites. Successful operation of the equipment encouraged us to expand the telemetry system to allow remote data collection from fifteen locations during the second winter of operation. (Figure 9)

A block diagram of the telemetry system used in our first winter of operation is shown in Figure 10. The remote stations (RTU's) on the ice were controlled by manual operation of a master control panel situated in Inuvik, 80 miles distance. In the standby mode, the receiver was the only device drawing current from the batteries. Any of the three analogue readings could be interrogated by the appropriate selection at the master control. Each analogue signal transmitted by radio was received by the master, converted into digital form, displaced visually, and printed on the teletype unit. With this system, manual interrogation from Inuvik was possible at any time but was performed routinely at daily intervals. Also, each day the tape containing the data was transmitted to Calgary via the telex. In this mode the system was successfully operated during the period February to May, 1972. Manual readings obtained during visits to the sites agreed exactly with the values obtained via the telemetry system.

Of the three data channels, two were generally used for ice movement, and the third for some other parameter; e.g. ambient temperature, housing temperature, battery voltage. At one location, wind speed and direction were measured leaving just one channel for ice movement.

VHF radios used during the first winter had good range but were subject to noise. In the second winter of operation, it was decided to change the system over to use UHF radios. This change also brought the ice movement system into line with our other data gathering network in the Mackenzie Delta area (see Figure 11). Use was made of an existing repeater station (Taglu) but to get the required range offshore, an additional repeater was added on Hooper Island. (This repeater has subsequently been used for other data gathering programmes.)

To accommodate the additional sites mentioned earlier, the master terminal was expanded from 10 to 20 address channels. An automatic interrogator was also added which was programmed to call up the remote sites at one hour intervals. An additional interface unit was provided so that the ice stations could be interrogated directly from Calgary (1500 miles distance) via a teletype line.

The bulk of the data, however, was stored on paper tape and shipped to Calgary by air at regular intervals. In Calgary, the data was fed into a master data file in the company's computer.

During the second winter of operation, a total of 12 telemetered sites were installed in the water depth range 8 to 100 feet, (see Figure 9). Sites 12, 14, and 15 were outside the range of the telemetry system and chart recorders were placed at these locations. In addition to movement, the following parameters were also measured: ambient, ice and housing temperatures, battery voltage, tide, wind speed and direction.

Heavy-duty lead acid batteries with a total capacity of 200 ampere hour were found to be satisfactory, for about 3 months operation. Wind chargers were installed during the second winter. They did not perform well but we have now diagnosed the problem and intend to try the chargers again next winter.

Installation and Logistics

During the first winter, installation of the sites commenced about mid January. The time required for installation varied between about two to five hours for each location. However, short daylight hours and bad weather stretched out the installation period to about 20 days. On the smooth land fast ice, we found it possible to use a fixed-wing aircraft equipped with skis for the installation period. However, subsequent visits to the sites became more and more difficult with the fixed-wing aircraft due to rough patches of drifted, hard-packed snow and we switched to using a helicopter.

Due to the increased number of telemetered sites, logistics problems were increased during our second winter of operation. However, good weather and an experienced crew resulted in very quick installation. In order to acquire movement data in the early part of the winter, the first five sites were installed in November. At that time, the ice was only about 15 to 20 inches thick and there was much open water outside the 15 to 20 foot water depth.

At each telemetered site about 1500 pounds of equipment was installed. There were five basic packages: two reel assemblies plus covers, an electronics package (2.5 x 2.5 x 2.5 feet), a battery box weighing 550 pounds (2.5 x 2.5 x 2.0 feet), and a generator tower.

Resolution Accuracy

The resolution of the system is strongly influenced by the horizontal offset and vertical distance between the bottom of the tube and the anchor. The worst situation is when the system has just been installed with no offset and the distance between the bottom of the tube and the seabed is not small. The table below shows typical accuracy of resolution when there is no initial offset and there is 10 feet from the base of the tube to the seabed. The values below also assume that changes in tape length of ± 1.0 inches can be detected (which is reasonable for both manual and telemetered readings.)

Total Horizontal Ice Movement (feet)	Resolution Error (%)
1	±100
2	± 40
3	± 18
4	± 10
5	± 7
10	± 2
20	± 1
< 20	< ± 1

The table above shows that accuracy of resolution improves as the amount of offset or ice movement increases. Remember that the values given above are for total ice movement and not change in ice movement.

CLOSURE

I have briefly reviewed how the motions of land fast ice can influence offshore resource development, and the techniques which are being used to study these motions. Because of the way the projects described in this paper have been sponsored, I cannot give at this time any details of the movements which have been measured. I do hope, however, that this paper will stimulate interest in the topic which previously has been somewhat neglected. For potential researchers perhaps my paper will help in selection or design of equipment. Further details of the equipment can be made available on request. The causes of movement of fast ice, and its correlation with winds, temperatures and currents, etc., is an area I have purposely avoided discussing in any detail. Our work has indicated that this is a complex problem; there is no simple correlation, and much work needs to be done before an understanding is gained.

ACKNOWLEDGEMENTS

The field work described in this paper was sponsored by Imperial Oil Limited and other member companies of the Arctic Petroleum Operators Association. I would like to thank those people who contributed to the work, especially those who worked in the field under trying conditions.

REFERENCES

1. Cochard, C., "Problems of Drilling Offshore: New Types of Platforms", Paper 206, Fifth International Congress, FFEN, Le Havre, France (May 1973)

2. Gerwick, B.C., Lloyd, R.R., "Design and Construction Procedures for Proposed Arctic Offshore Structures", Offshore Technology Conference, Houston 1970. OTC 1260

3. Roots, E.F., "Shore Fast Sea Ice", Workshop on the Action of Ice on Structures, Ottawa, November 1970. National Research Council Technical Memorandum No. 101

4. Roots, E.F., Cooper, P.F., "The Movement of Constrained Sea Ice", Workshop on the Action of Ice on Structures, Ottawa, November 1970. National Research Council Technical Memorandum No. 101

PROPOSED ARCTIC DRILL SYSTEM
FOR LAND FAST ICE

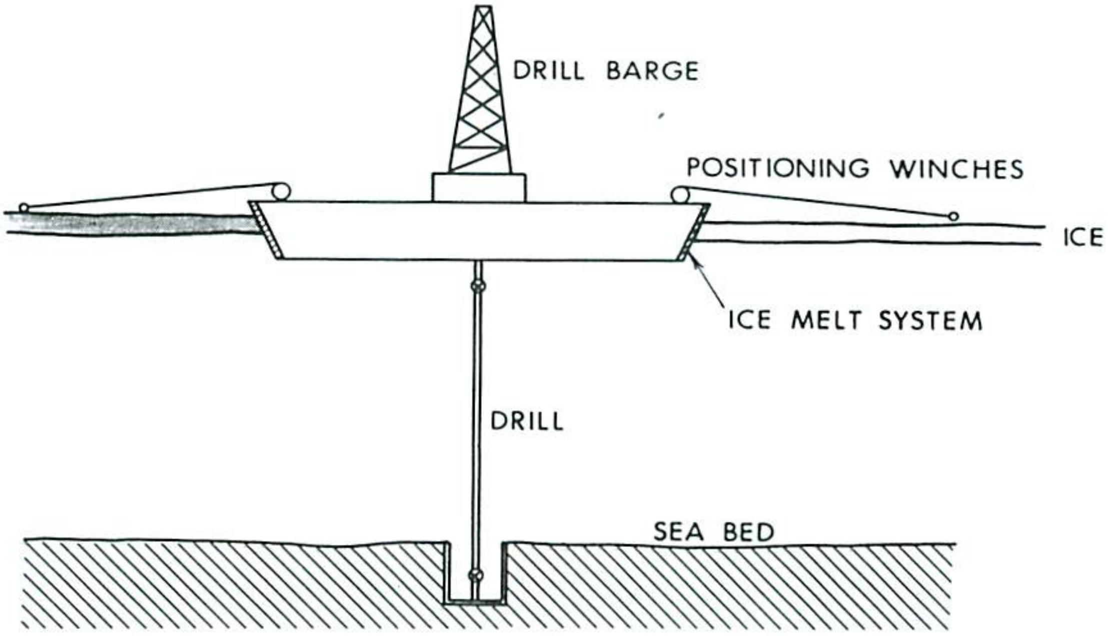
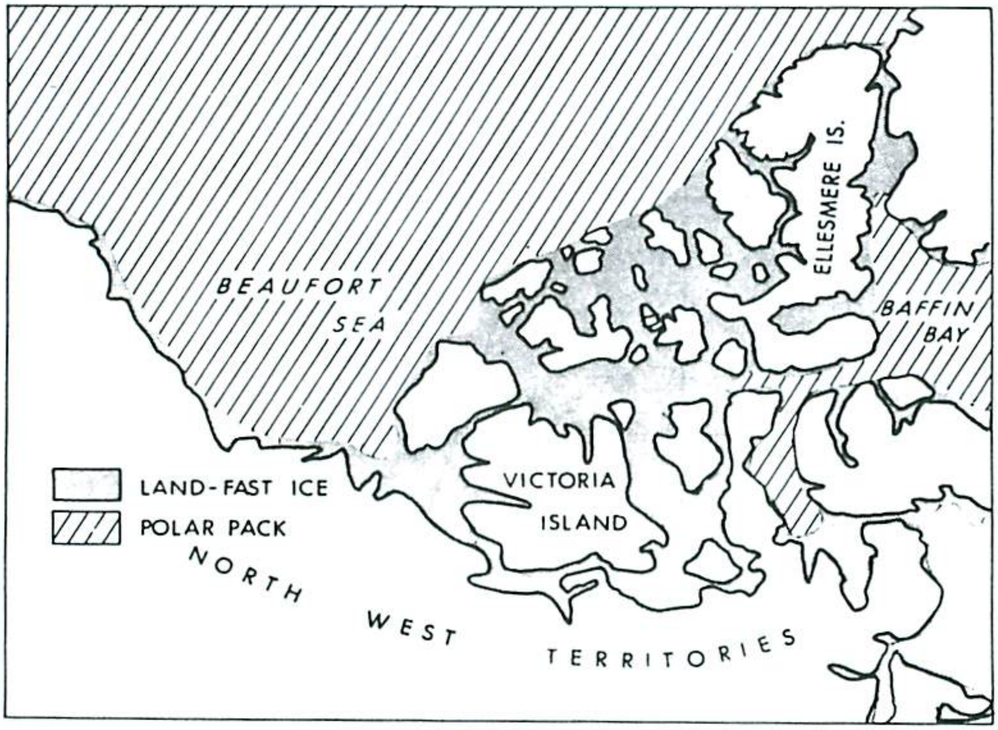


FIGURE 1



EXTENT OF LAND-FAST ICE IN WINTER

FIGURE 2

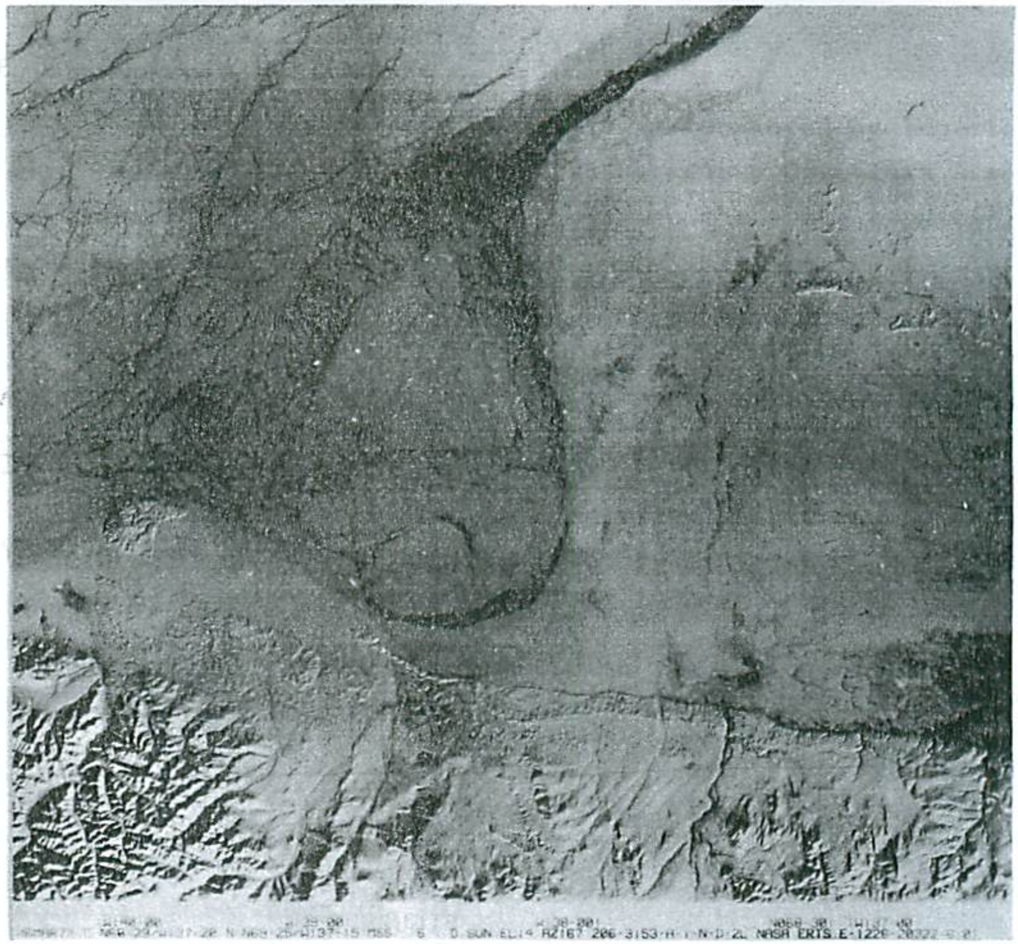
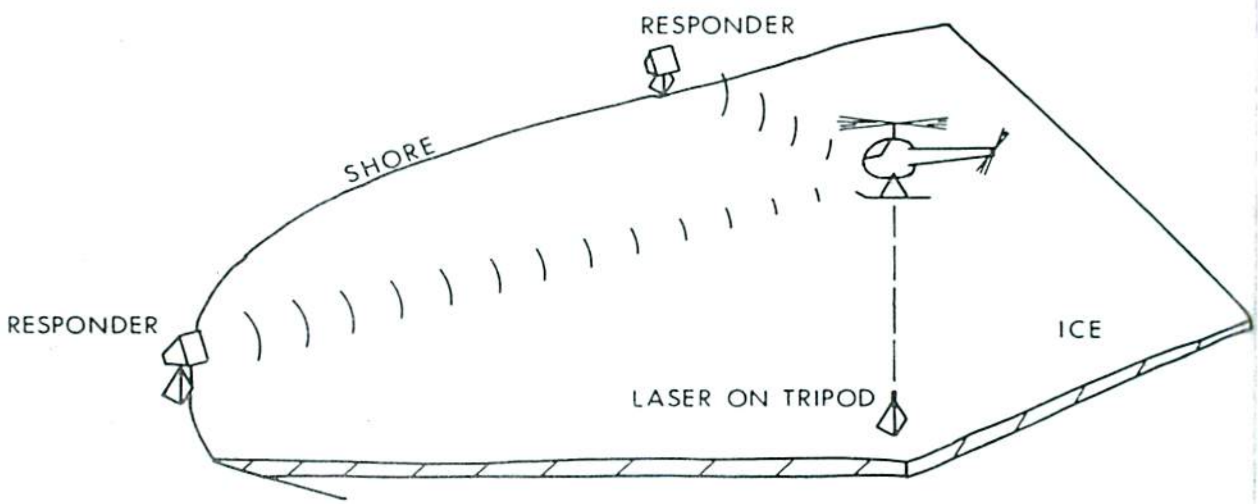
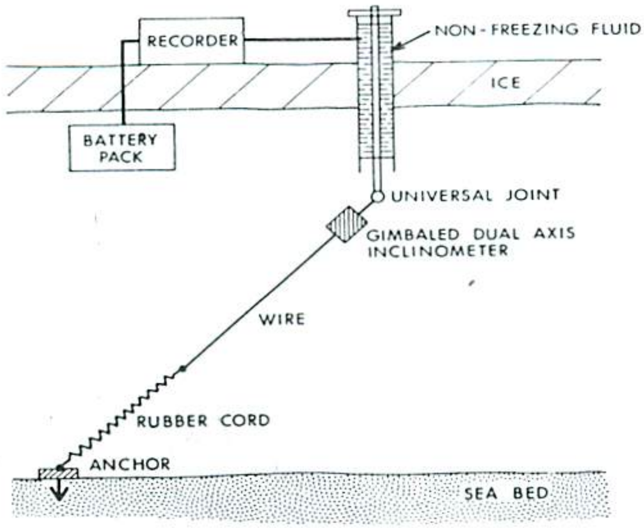


FIGURE 3 - SATELLITE PHOTO - MACKENZIE DELTA



MICROWAVE POSITIONING SYSTEM
USING LASER VERTI-SITE

FIGURE 4



INCLINED WIRE SYSTEM

FIGURE 5

ACOUSTIC RANGING SYSTEM (O.S.I.)

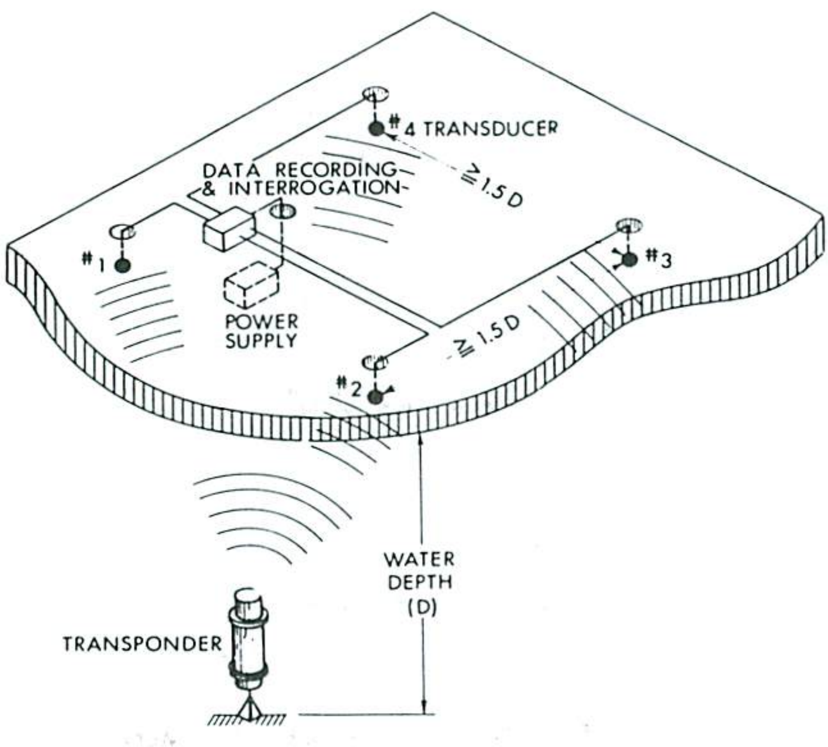
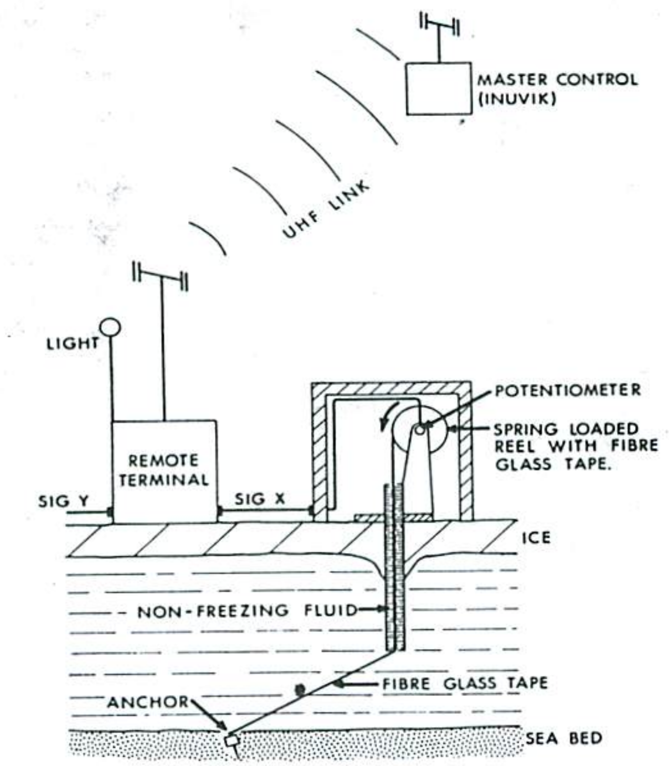
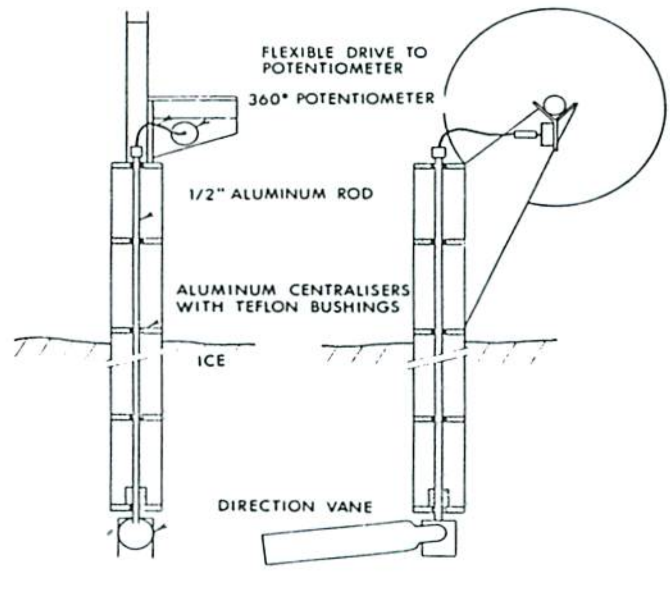


FIGURE 6



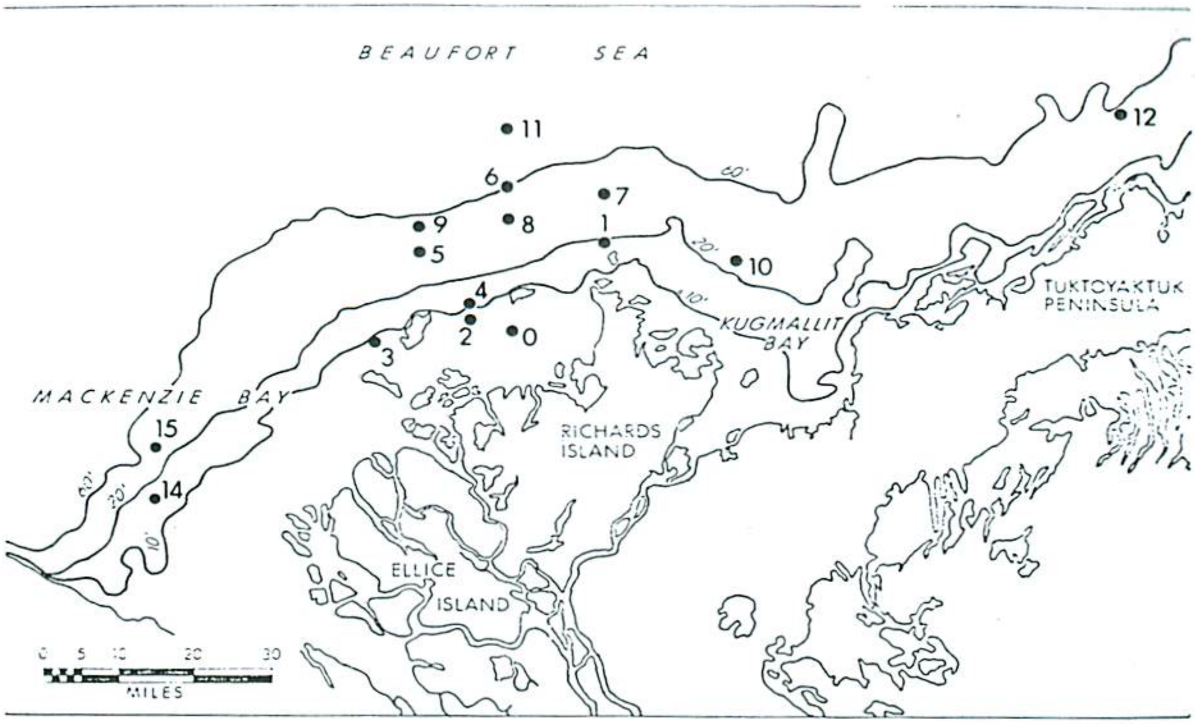
SCHEMATIC OF SYSTEM

FIGURE 7



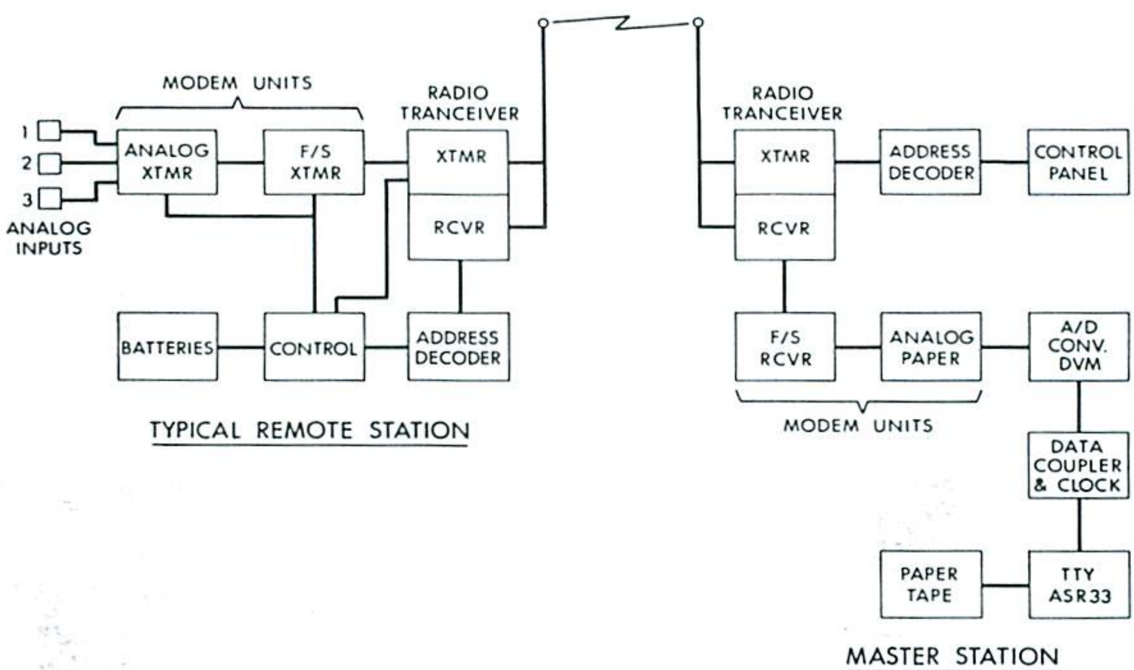
DIRECTION ARM FOR ICE MOVEMENT SITES

FIGURE 8



ICE MOVEMENT SITES 1972 - 73

FIGURE 9



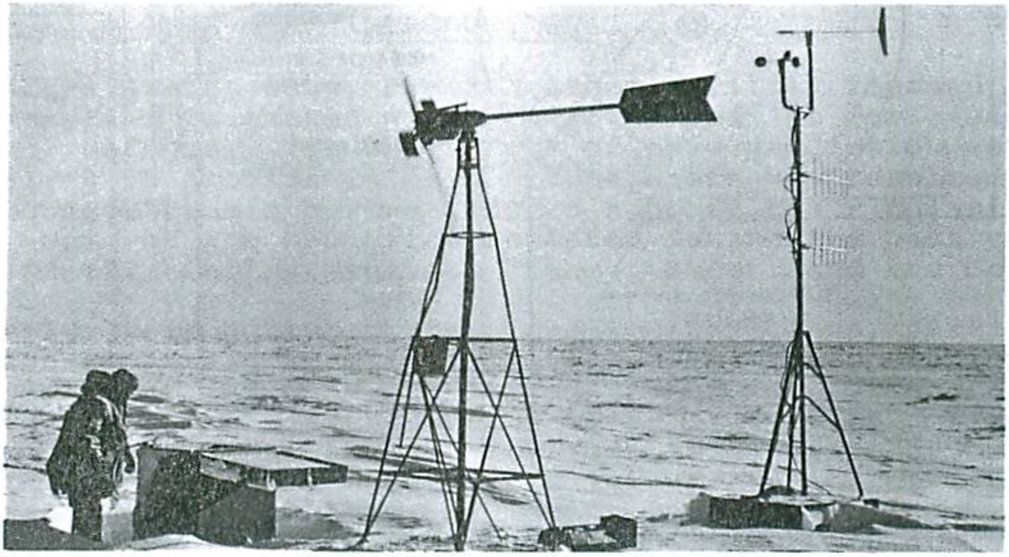
BLOCK DIAGRAM
SHORE-FAST ICE MOVEMENT - TELEMETRY SYSTEM

FIGURE 10

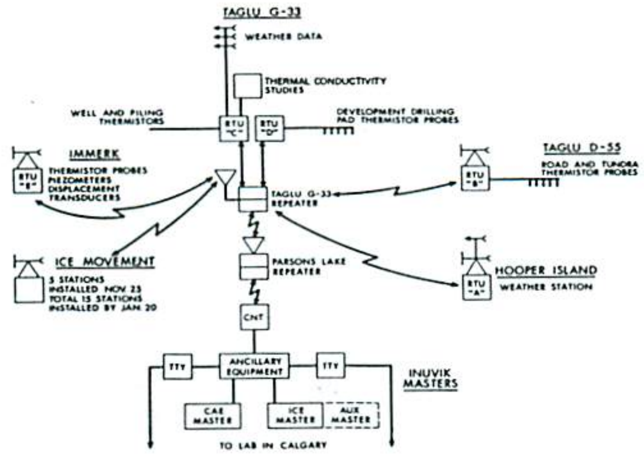
A REEL ASSEMBLY

SITE NUMBER 5

SITE NUMBER 9

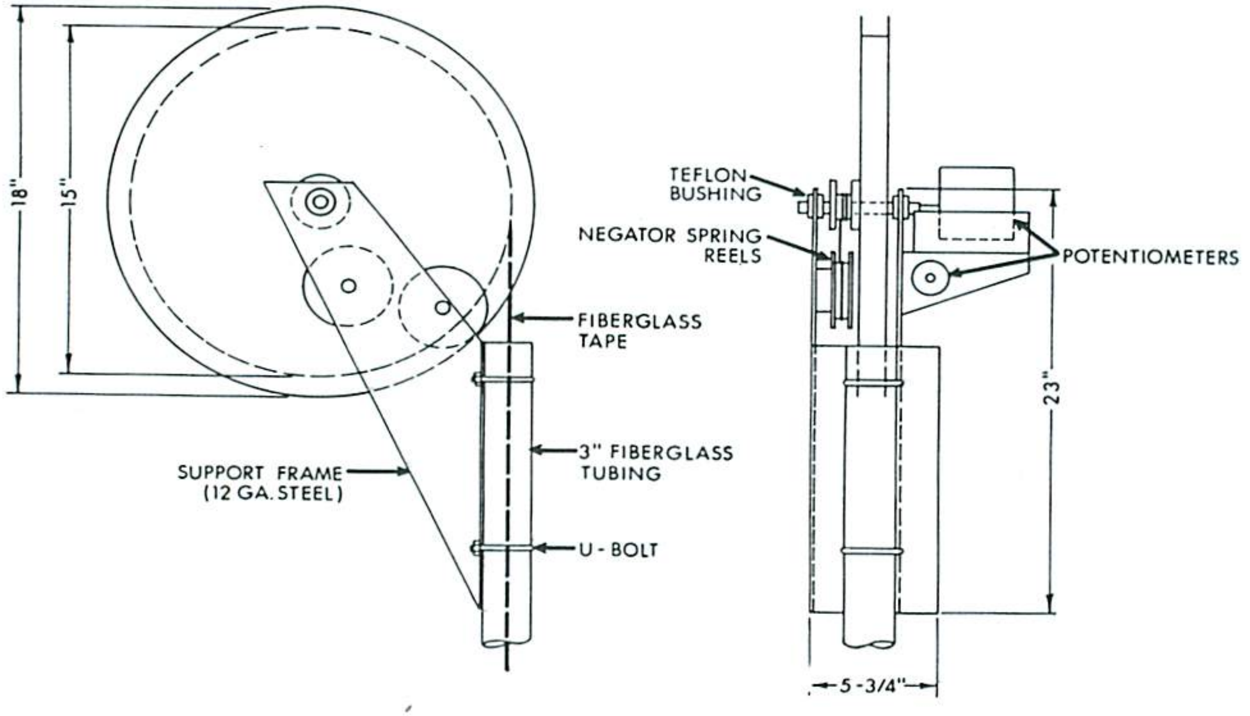


SITE NUMBER 4



ARCTIC DATA ACQUISITION SYSTEMS

FIGURE 11



MECHANICAL REEL FOR ICE MOVEMENT SITES

FIGURE 12