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**ARCTIC ICE ISLAND AND SEA ICE MOVEMENTS AND
MECHANICAL PROPERTIES**

First Quarterly Report for the Period October 1—December 31, 1983

**By
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FIRST QUARTERLY REPORT
1 October - 31 December 1983

Submitted to

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I. BACKGROUND

Ice Islands

The shelf ice along the north coast of Ellesmere has been recognized as a source of large tabular icebergs, termed "ice islands", for many decades. These features are carried by the sea ice around the Arctic Ocean and have been observed to be grounded occasionally in the deeper waters of the Alaskan shelf. When ice islands ground, they may break up into several large fragments, each of which is of sufficient size to constitute a physical hazard to offshore operations. Such ice island fragments were documented in aerial photographic surveys along the Beaufort Coast during the interval 1972-1976 (Imperial Oil Ltd., 1976). Because ice islands may be as thick as 60 meters, and are broad enough to concentrate pack ice stresses in front of a structure, they represent the most severe ice hazard as yet recognized for Arctic offshore oil and gas structures. However, their frequency of occurrence, presently unknown, is hopefully low.

The Imperial Oil study of grounded ice island fragments found 433 fragments during 1972; the largest was over 1.6 kilometers in length, near Flaxman Island in the Beaufort Sea. In 1973, 299 islands and fragments were observed; about 65% of them were grounded in 25 meters to 35 meters of water, with the remainder grounded in less than 20 meters of water. In 1974, 27 ice island fragments were observed, and in 1974, ten fragments were grounded in 30 meters of water north of Prudhoe Bay.

There have been many large ice islands discovered since 1946 (Koenig, 1951). For example, on August 14, 1946, the ice island T-1, measuring approximately 15 by 18 nautical miles, was discovered about

300 miles north of Point Barrow. Ice island T-2 was found July 21, 1950, at 86°40'N/167°00'E, and had a size of 17 by 18 nautical miles. On July 29, 1950, the most famous ice island, T-3, was discovered at 75°24'N/173°00'W; measuring 4.5 by 9 nautical miles in size. Drift velocities of 1-2 nautical miles per day have been typically reported.

There was a massive calving event from the Ward Hunt Ice Shelf at the mouth of Disraeli Fjord on Ellesmere Island from February 6 to March 6, 1962, in which five major ice islands were created, designated as WH-1, WH-2, WH-3, WH-4, and WH-5. The report by Holdsworth (1971) presents a map (Figure I 1-1) showing the initial location of these ice islands. The easternmost island, WH-5, moved eastward to Robeson and Kennedy Channel, where it passed between Greenland and Ellesmere Island becoming lodged at Hans Island in the Channel. The others moved westward and entered the Beaufort Sea where they drifted for some time. Drift rates of about 0.5 km/day were typical. A total ice island area of about 600 km² was embodied in these five ice islands. The calving event has been correlated with abnormal tidal excursions and a small seismic event in the region. Observations over the past century have been sporadic, and some early authors expressed the opinion that these ice shelves were static. However, recent information shows this to be incorrect. Between 1962 and 1966, the M'Clintock and Ayles ice shelves broke up (Hattersley-Smith, 1967). Ice islands were reported along the west coast of Axel Heiberg Island, in Norwegian Bay, M'Clintock Channel, Queen Maud Gulf, Prince Patrick Island, Otto Fjord, and Sverdrup Channel. Regrowth of the Ward Hunt Ice Shelf, and of a shelf in Nansen Sound, by bottom ice accretion, has been reported (Holdsworth, 1971). The flow of fresh melt runoff water into these fjords, followed by

trapping of the fresh water between the cold ice above and the cold (-1.8°C) sea water below, is probably responsible for ice shelf regrowth. Production of ice islands is perhaps a random process, but there may be time-and-space clustered events.

Discovery of ice islands has been a matter of opportunity; Zimmerman (1971) discovered one 100 km northeast of Barrow on March 31, 1971, which measured 7.2 by 2 km. They have often been used as drifting scientific stations (T-3, ARLIS-II) since they offer great stability. Trajectories of drifting scientific stations help define the two main features of ice island drift: The Beaufort Gyre, circulating clockwise, carries ice islands from northern Canada to the Alaskan Beaufort Sea. The gyre is circular and can "store" an ice island for several drift revolutions. The Trans-Polar Drift Stream, extending from the western Chukchi Sea across the Pole and towards the North Atlantic, provides a mechanism for removal of ice islands from the Gyre, (as is presently the case with T-3).

The earliest reference to what may have been an ice island is by Parry (1821) on his first voyage in 1819-20. He describes an immense flow in M'Clure strait which ... "was covered with large hummocks, giving to its upper surface the appearance of hill and dale... The thickness of this floe at its nearest edge was 6 or 7 feet above the sea, and ...the whole thickness would appear...to have been from forty to fifty feet. But the hummocks were many of them at least from fifteen to twenty-five feet above the sea...". It seems likely that this was a very old multi-year hummock field. Greely (1886) notes in his log several sightings, one near Cape Baird in August 1883, an immense flow "fifteen miles long and of unknown width. Another floe, between Cape Beechy and

Cape Sumner, was of such extent that a sledge party was nearly two days passing over it. The surface of such a flow resembles closely a piece of rolling country...has its hills and dales, its water-courses and lakes; in fact, it is an island where ice replaces earth." Sverdrup (1904) describes some "old polar ice" in Eureka Sound "with enormously high melted-off ridges and deep dales."

Storkerson and four others drifted on an ice floe in the Beaufort Sea for six months in 1918 that was "a large island of ice about seven miles wide and at least 15 miles long." The topography was gentle hills and ridges with small lakes like "...prairies I have seen in the midwestern United States and Canada...". They noted that their movement was less influenced by the wind than the pack ice surrounding them, so there was always open water downwind from the island. They estimated the thickness to range from 20 to 60 feet. The topography and drift pattern strongly suggest that they were on a drifting ice island. Another report was given by Takpuk, an Eskimo, (in Stefansson, 1934) of an island of ice about one half mile across in the Beaufort Sea. It was north of Camden Bay, in 120 feet water depth. It had a gently rolling surface sloping up to a small hill at one end. A large area of the hill was covered with soil supporting grasses and moss.

A thorough search of RCAF aerial photos (Greenaway, 1952) yielded 59 possible ice islands as well as many more small fragments. Most of the new ice islands were in the Canadian Archipelago and most of the larger pieces were grounded.

More recent references to ice islands come from Russia. "In October 1943, three kilometers to the north-northwest of Mys Chelyuskin, a flat-topped iceberg was discovered, 1,500 meters long, 400 meters

wide, and rising 10 meters high out of the sea," (Zubov, 1948, quoted by Dunbar, 1952). Zubov also reports that icebergs were seen off the east coast of Ostrov Vrangelya in 1946, aground in shoal water, and off the west coast of the island in 1947.

Both Pelham Aldrich of the Nares Expedition (1875-76) and Peary (1907) traversed the ice shelves of Ellesmere Island, including the Ward Hunt Ice Shelf, and reported the long, prairie-like swells of its surface (Dunbar 1952). Both of these explorers reported Yelverton Bay full of this rolling ice topography, yet recent air photos show that this is not the case. It is thus quite probable that Yelverton Bay has been a source of ice islands during the past century.

The number of islands presently in the Beaufort Gyre is a factor in determining the probability of ice island encounters with offshore structures. Several years may be required to transit the Gyre, depending upon the duration of the time an ice island is grounded on the shelf, and several transits may occur. An inventory of ice islands is difficult, even by satellite imagery, but may be done for those regions covered by Landsat (south of about 80°N), and those ice islands larger than about 0.1 km. Cloudy weather prevails much of the time, and the planned use of active microwave synthetic aperture radars on future satellites is expected to provide a much-improved opportunity for the location of existing ice islands. The region of ice island generation, along the north coast of the Canadian islands and Greenland, is not imaged by Landsat because of the satellite's orbital characteristics. Therefore, the ice island generation rate can be determined only by repetitive aerial photography and surface traverses. Subsequent

trajectories can be determined by satellite-positioned stations emplaced on newly-discovered ice islands.

Figure I 1-2 shows an example of the appearance on aerial photography of an ice island which has divided into fragments upon grounding. Clusters of ice island fragments thus created are subject to irregular release and resumption of drift, depending upon the degree of initial grounding; the ablation rate which reduces freeboard, increasing buoyancy; the storm tides in the area; and the degree to which pack ice forces are brought to bear against each fragment. This generally results in a sequential dispersal of ice island fragments. The size and spatial distribution of fragments resulting from the breakup of major ice islands is an important part of the total statistical analysis of the encounter probability with an offshore structure.

The risk of impact on an offshore structure by an ice island has been addressed in a generalized mathematical way in a recent paper by Dunwoody (1983). His paper lays a foundation for the statistics of ice island encounters but requires appropriate input data obtained from this project. Quoting from his final discussion:

"Finally with regard to the ice island statistics used, the statistical picture for ice islands is still very sketchy. Therefore, the risks of ice island impacts which can be calculated are very approximate. There have been just too few ice islands in the Beaufort Gyre to develop a complete statistical description. Much of the picture which has been created has been based on inference from related phenomena and physical understanding of the processes at work. Short of discovering a number of new ice islands, the greatest improvements to the statistical description will come from ongoing research into the growth of the ice shelves, the dynamics of ice shelf breakoffs and the dynamics governing the motion of an ice island within the polar pack."

Based upon the historical evidence summarized above, it appears that Dunwoody's remark about "few ice islands" is not correct, but

rather there have been many ice islands observed in the past century. The sanguine point is that the many ice shelves produce ice islands of thickness varying from a few meters up to about 60 meters, with the massive Ward Hunt Ice Shelf probably producing the thickest ice islands. The distribution of ice island thicknesses as well as their size, initial position, date of generation, trajectory, grounding, fragmenting, and ablation, all combine to yield the probability of encounter of an ice island with an offshore structure. The definition of ice island must include ice from any of the shelf ice locations.

Chukchi Sea Pack Ice Edge Intrusion

The design and scheduling of arctic offshore operations depends a great deal on the possibility of the presence of ice. A significant portion of the U.S. part of the Chukchi Sea is never statistically outside the pack ice limit. The other portion contains areas which are outside the statistical mean of the pack ice limit for periods ranging from a few weeks to a few months. However, within the statistical pack ice limit a given location will have a finite probability of remaining ice free for any (reasonable) stated period, and outside the statistical pack ice limit a given location will have a finite probability of experiencing a pack ice incursion during the statistically ice free period. For these reasons, probabilities of ice free periods cannot be based on average pack ice edge locations. This research activity is designed to address this problem and provide users with realistic values for ice free operating periods in the Chukchi Sea.

Mechanical Properties of Sea Spray Ice Bonds to Structures

Solutions to the problem of accretion of sea-spray ice on marine structures and ships are especially important when the production of offshore oil reserves in the Bering, Chukchi, and Beaufort Seas is undertaken. Fishing boats in northern latitudes of the Atlantic and Pacific Oceans and contiguous seas have usually combatted this serious hazard by departing from areas of high winds, high waves, and cold air temperatures; each year, in spite of this, reports of fishing boats presumably lost to spray ice buildup are received. A fixed offshore production structure cannot leave its site, and the workboats servicing it can only defer their services for a limited time, so one must expect ice accretion and learn to design to minimize and/or accommodate it. Reports by Kovacs (1982, 1983) have described spray icing thicker than 30 cm on Fairway Rock in the Bering Strait and on King Island in the Bering Sea. Anecdotal evidence has corroborated his observations; this ice thickness has been found on seaside cliffs at the Pribilof Islands in the Bering Sea, (St. George Basin Synthesis Meeting, 1981), and after a severe fall storm in the Canadian Beaufort Sea at the Tarsuit artificial island site (Offshore Technology Conference, 1983). Ice accretion to a height of 50 meters above the waterline has been observed in some of these locations (Kovacs, 1982, 1983). A calculation of probability of occurrence for a location in the Bering Sea has been made by Sackinger (1981) who concluded that there is a 9% probability that spray ice accumulation -- at the rate of 3.5 cm to 14 cm per day -- will take place during the month of January in the Bering Sea near the Pribilof Islands. Comprehensive reviews of the environmental conditions causing spray ice formation have been made by Carlson et al., (1982), by

Wise and Comiskey (1980), by Jørgenson (1982), and by Minsk (1977). It is not the objective of this review to summarize all of the environmental observations reported in the reviews cited above; the interested reader is referred to those for details.

However, the subject of ice removal is of ultimate importance. Methods tried include thermal heating, chemical liquids, flexible surfaces, infrared, pneumatics, vibrations, water-jets, and special paints (Jørgenson, 1982). Most trials involving coatings were done at least a decade ago, and were unsuccessful. Recently-developed coatings for lock walls are possible candidates. Combinations of modern coatings and suitable geometrical designs have yet to be tried, and since they are inherently reliable and passive (not requiring active energy input) they show great promise. A fundamental requirement for success for all approaches toward a solution is to develop a method for evaluating shear and tensile strengths of the interface bond between the sea spray ice layer and the structure or ship surface. A second more detailed task is to then measure the mechanical properties of this bonded layer for a variety of candidate coatings, as functions of temperature, loading rate, strain rate, salinity, and ice type. Realistic samples obtained under natural conditions must be used. Shear and tensile strength and shear creep should be measured. This has not been done, and it is the task of this program to develop these measurement techniques and to perform such measurements. A visco-elastic model of the mechanical properties of the interface region will subsequently be developed.

II. RESEARCH ACTIVITIES IN FIRST QUARTER

1. Ice Islands

As soon as possible after the inception of the program on October 1, 1983, a conference was held with the Program Manager at Morgantown, W. VA., to plan details of the research for the coming year. With respect to the ice island portion of the project, it was decided (1) to use aerial photography, satellite imagery, and all available historical records to establish a time history of all of the ice shelves of Ellesmere Island; (2) to establish positioning buoys on the existing ice islands to track their trajectories daily and to telemeter daily barometric pressure and temperature, via System Argos; (3) to relate geostrophic winds to the observed trajectories; (4) to begin to build a pseudo-random model for ice island motion over the long term which would enable a determination of the probability of interaction between ice islands and offshore structures. Deliberately excluded from the scope of this project were questions relating to the causes of ice island calving from the parent ice shelf, the geomorphology of the ice shelves, and also specific studies of the ice islands themselves (ice properties, etc). Moreover, countermeasures to mitigate ice island collisions with offshore structures were excluded. Although such research is important and worthwhile in obtaining a total solution to the overall ice island problem, it is beyond the scope and the financial resources of this particular project.

Plans were also briefly reviewed for the portion of the project which is to describe the statistics of the Chukchi Sea pack ice edge incursions, from satellite imagery.

The third part of this project is directed towards the measurement of the shear strength of the adfreeze bond between spray ice accreted on structures and ships and the various coatings which could be used on them. This has obvious application to the safety and more economic design of offshore structures, workboats, tankers, fishing vessels, and harbors. The plan for the first year included (1) choice of substrate geometry; (2) field deployment of substrates to assess proper fixtures for ice sample collection; (3) design of a loading apparatus for testing the shear strength of the bond.

After the planning meeting with the Arctic/Offshore Program Manager, Dr. Harold Shoemaker, an aerial surveillance of the Ellesmere Island Ice Shelves was carried out on October 19, 1983. A charter flight of a deHavilland Twin Otter originating at Resolute, N.W.T., with refueling stops at Eureka and Tanqueray Fjord, was used. A first objective was to locate the ice islands recently reported as calved from the Ward Hunt Ice Shelf (Jeffries and Serson, 1983), the largest of which (3 km x 9 km in size) was chosen by Dr. George Hobson as a site for a positioning buoy, which he installed on August 11, 1983. Thanks to the courtesy of Dr. Hobson, he informed us that on 13th October 1983 the large island (4 km x 8 km in size) was at 82°32'N, 86°06'W, just to the north and west of Yelverton Inlet. We flew to that location but were not able to locate the large island due to the presence of a cloud cover at about 250 meters altitude. However, several other ice islands

were observed clustered in the region, and were photographed. (In retrospect it appears that these were northeast of the large island).

The cluster of ice islands was composed of pieces of obviously different origin. The surface topography and the freeboard were the two obvious characteristics upon which the distinction could be based. An ice feature was termed an "ice island" if it was obviously of greater freeboard, if it was not cracked, and in fact if it induced fracture of the sea ice around it.

The first such island (denoted "Alpha") was roughly circular, some 2.5 km in diameter, at $82^{\circ}36.5'N, 85^{\circ}59.1'W$.; photographs taken of this are not available due to a film advance problem which was detected and corrected. The surface topography included a few higher regions with edge freeboard varying from about 2 meters to 5 meters, as estimated from an altitude of 100 meters. It's location on that day at 1530 GMT is shown on the map, Figure II-1.

A second ice island (denoted "Beta") was observed at $82^{\circ}36.8'N, 85^{\circ}50.1'W$ as shown in Figures II-2-4. The boundaries of this large floe are irregular, suggestive of old multiyear ice ridges, especially noticeable in Figure II-3. This island was obviously thick but it's freeboard was hard to judge from the air because of the multi-year ridge and rubble at it's boundaries. The cracks in the pack ice around it (Figure II-3) suggest that the island's greater draft causes an additional current-induced drag distinct from that imposed upon thinner pack ice. This is also noticeable in Figure II-4 and II-5, but not in Figure II-6 taken farther around the island, from $82^{\circ}38.4'N, 85^{\circ}54'W$. The absence of rolling surface topography implies that this island Beta did not originate from the Ward Hunt Ice Shelf,

but may be multi-year ice which accumulated in the mouth of one of the inlets. Whether it's thickness is due to underice accretion of platelets from fresh water runoff, or simply is due to a heavy and very old multi-year ice rubble field, would best be determined by detailed surface and sub-surface examination.

A third ice island with one sharply-defined edge of approximately five meters free board was discovered nearby, denoted "Gamma", and shown in Figures II-7-10. The edge in Figures II-7 and II-8 suggest that the island Gamma broke away from some existing shelf. Rolling surface topography was not noted however. The thickness of this island tapers gradually to that of normal pack ice as shown in Figure II-9 and II-10, where the opposite boundary of Gamma is shown. The extreme tip of that feature is shown in Figure II-11. This fragment illustrates the fact that ice floes or ice islands can have quite variable thickness across their diameter.

The fourth ice island, denoted Delta, is shown in Figures II-12-16. This is a more classic example of an ice island which has a distinctive edge with 5-6 meters freeboard (Fig. II-13-14). Furthermore, two parallel valleys are visible on Figure II-13, and they are wide and well-developed. Clearly this is old shelf ice, and may be the smaller island reported by Jeffries and Serson (1983) as originating from the Ward Hunt Ice Shelf. Open water is evident adjacent to it (Figure II-14). The roughly triangular shape (Figure II-13) was circled and opposite sides (Figure II-13 and Figure II-15) had the abrupt edge. However, the island appeared thinner on the third edge shown in Figure II-16.

In Figures II-17 and II-18, the boundary of another very old and integral multi-year floe is shown. This is of unknown thickness but because of the lack of a well-defined edge cliff we refrain from using the term "ice island" for this feature. It seems that this region of the pack can produce such very old and obviously strong multi-year floes which may pose a hazard to offshore structures of severity comparable to the ice islands.

To summarize, then, at least five ice islands and several thick multi-year floes were found clustered in the vicinity of 82°36'N, 85°54'W, during the reconnaissance flight. If one assumes that these initially will follow the same approximate path as the larger, instrumented ice island, then these afford an opportunity for emplacement of additional positioning buoys, and the dispersion of such a cluster can be observed as they make their way towards the Beaufort Sea. This is planned for later in 1984.

The delineation of the edge of the ice shelves can best be discussed in terms of zones. The zones observed may be seen on the map of Figure II-19. There are:

- Yelverton Bay
- Unnamed Inlet (from Hansen Pt. to Cape Evans)
- Milne Ice Shelf (from Cape Evans to Cape Egerton)
- Ayles Ice Shelf (from Cape Bicknor to Cape Fanshawe Martin)
- C. Fanshawe Martin to Cape Richards
- Bromley (from Cape Richards to Bromley Island)
- M'Clintock Ice Shelf (from Bromley Island to Cape Discovery)
- Ward Hunt Outer Ice Shelf (Cape Discovery to Cape Albert Edward)
- Ward Hunt Inner Ice Shelf (Marvin Islands to Disraeli Fjord)
- Disraeli Fjord
- Markham Fjord Ice Shelf (Cape Nares to Cape Columbia)
- Parr Bay Ice Shelf (Cape Aldrich to Stubbs Point)
- Doidge Bay Ice Shelf (Stubbs Point to Good Point)
- Giffard Ice Shelf (Good Point to Cape Colan)
- Clements Markham Inlet (Cape Colan to Cape Hecla).

Navigation equipment on the aircraft accumulated errors during the flight and although the position of each photo was recorded, upon retrospective analysis these data are in error by as much as ten kilometers and are therefore not discussed below.

The eastern part of Yelverton Bay was smooth ice as shown in Figure II-20. A closer view of the ice at the shoreline at the east edge of the Bay is given in Figure II-21. Both photos were taken from 500 meters altitude, as was Figure II-22 looking more towards the southeast. In Figure II-23 these latter two photos are combined to give a wider view of the ice rise on that point of land separating Yelverton Bay from Unnamed Inlet.

The thick shelf ice in Unnamed Inlet is shown in Figures II-24 and II-25, which are combined in Figure II-26. There is smooth thinner undeformed shelf ice in the foreground as well, showing a rolling topography which implies that it has survived several summer melt seasons. The ice rise at Cape Evans is shown in Figure II-27.

Fog obscured the Milne Ice Shelf, and it was necessary to fly over the pack ice to Cape Egerton, shown in Figure II-28. The rolling topography in the right side of Figure II-28 shows that the Milne Ice Shelf is well-developed. Coming closer to Cape Egerton (Figure II-29) the ice shelf is smooth but extending about 1-2 km. seaward from the point of land.

The Ayles Ice Shelf is quite large and smooth, appearing to be only slightly thicker than the adjacent sea ice (Figures II-30, II-31, II-32). At Cape Fanshawe Martin (Figure II-33) the ice is about 1 km from the shoreline, extending into Bromley Island (Figure II-34).

The M'Clintock Ice Shelf (Figure II-35) was also level, flat, and very large, with the sea ice boundary extending across the points of land.

The Ward Hunt Ice Shelf begins with Figure II-36 and in this westernmost part is thick, level, with a well-defined seaward boundary. Remarkable along all of these ice shelf/sea ice boundaries was the complete absence of open leads, shear ridges, compressive ridges, or any other evidence of sea ice activity. Clearly, the sea ice in this region could be termed a "stagnation zone" in contrast to the usual pack ice movement. Of course, sporadic movements occur producing small local rubble, but no evidence of extended ridge or leads systems was apparent. As one moves farther east on the Ward Hunt Ice Shelf, the rolling topography parallel to the coastline is observed (Figure II-37). The camp maintained by the Canadian Polar Continental Shelf Project at 83°05'N, 76°36'W, was visible and is shown in Figures II-38 (looking north) and II-39 (looking south).

The Ward Hunt Ice Shelf east of the camp is shown in Figures II-40, II-41, and II-42, taken from the edge of the ice shelf, progressing eastward. The ice rise adjacent to Ward Hunt Island is shown in Figure II-42. At the edge of the shelf, between Ward Hunt Island and Cape Albert Edward, the visibility improved and the location described by Jeffries and Serson (1983) as the likely source of two ice islands was photographed (Figure II-43). From that photo, it appears that the angle between the ice surface undulation direction and the ice shelf edge is roughly 30° at the breakout region. The ice islands thus generated could be expected to have their longest dimension at roughly the same angle with respect to the surface undulation direction. Cape Albert

Edward is shown in Figure II-43 and again in Figure II-44, where the adjacent multi-year sea ice floes are shown more clearly. A panorama of the Ward Hunt Ice Shelf is shown in the sequence of photographs of Figures II-45 through II-50, taken looking southeast, south, southwest, and west as one flies towards the ice shelf edge from the pack ice region. The shelf ice seaward of an imaginary line drawn from Cape Albert Edward to Ward Hunt Island can be considered as a potential source of ice islands, an area of some 100 km². An additional 200 km² of the Ward Hunt Ice Shelf from Ward Hunt Island west to Cape Discovery represents a potential source of ice islands. Causes of shelf ice separation from the shelf boundary region are as yet poorly understood, and deserve further study.

Entering the Disraeli Fjord, which has the Ward Hunt Ice Shelf at it's mouth, the rolling ice upper surface topography (Figure II-51) changes in periodicity (Figure II-52) until one passes the Marvin Islands (Figure II-53). At that point, the upper surface appears to be covered with a refrozen smooth ice layer penetrated by mounds of the ice sheet which survived the summer melt (Figures II-54 to II-57). The surviving network of mounds is more prominent at the center of the Fjord, as shown in Figures II-57 and II-58. This type of feature ends just seaward of the small island halfway into the Fjord (Figures II-59 and II-60). Farther down the inlet, the smooth ice is continuous (Figures II-61 to II-64) to the end of the Fjord. The glacier on the east side of the Fjord (Figure II-65) does not extend down to sea level at this time. A final view of the east side of Ward Hunt Ice Shelf, looking northeast from the mouth of the Disraeli Fjord, is in Figure II-66.

Proceeding east from Ward Hunt Ice Shelf along the coast toward Cape Nares, a portion of narrow shelf ice remains (Figure II-67) but soon disappears (Figure II-68). The next region of shelf ice is in Markham Fjord (Figures II-69, II-70, II-71) which seems to have flat, featureless ice on its western side and deep within the inlet (Figure II-69). The ice makes a gradual transition (Figure II-70) to rolling and old shelf ice on the eastern side of the Fjord mouth (Figure II-71). East of Markham Fjord, the sea ice comes close to shore between Cape Columbia and Cape Aldrich.

The region of Parr Bay, from Cape Aldrich to Good Point, does not have rolling ice topography as was indicated to exist in 1959 on the map of the area, but rather is flat (Figures II-72 and II-73). This is a region which may have produced ice islands during the past two decades.

The region from Good Point to Cape Colan, which is also shown on the map as possessing ice shelves in 1959, did not have old ice shelves, but rather has new smooth ice in the bays, with static old sea ice floes adjacent (Figures II-74 and II-75).

However, the shelf ice just to the west of Clements Markham Inlet, from Stuckberry Point to Cape Colan, is still evident as shown in Figures II-76 through II-80, which were taken in rapid sequence and with overlapping fields of view at that location. The rolling ice topography extends out into the edge of the mouth of Clements Markham Inlet. However, there is the appearance of new and somewhat deformed ice rubble in patches across the mouth of the inlet (Figures II-81 and II-82). Smooth, featureless ice of undetermined age and thickness covered the inlet from its mouth all the way to the glacier at the end of the inlet (Figures II-83 to II-91).

To summarize, there are several regions which show an indication of shelf ice departure, and are possibly reforming, since the 1959 survey. These include Yelverton Inlet, the outer edge of the unnamed inlet, part of Ayles Ice Shelf and Ward Hunt Ice Shelf, plus ice in Markham Fjord and from Cape Aldrich to Cape Colan. More data from the past two decades is being assembled to compare with this oblique photography taken October 19, 1983. Estimates of the time and position of ice island generation events will be made by comparing all available data. In addition, 1984 data will be compared with the October 1983 data given above, to determine the number and origination point of ice islands released this year.

The trajectory of the ice island tagged with an Argos buoy by Dr. George Hobson, of the Canadian Polar Continental Shelf Program is shown in Figure II-92 for the interval August 13 to December 23, 1983. Data has kindly been provided to us by Dr. Hobson. Many time intervals corresponded to pseudo-random motions, north of Phillips Inlet, whereas a second category of motion, rapid and parallel to the shoreline, occurred infrequently. We intend to try to distinguish the two classes of geostrophic wind patterns which are responsible for these two types of behavior, and to develop a quantitative relationship between the motions and geostrophic winds.

2. Intrusion of the Pack Ice Edge in the Chukchi Sea

The overall objective of this task is to investigate and analyze the causes and extent of summertime pack ice intrusions into the Chukchi Sea, which would interfere with exploration drilling and emplacement of

permanent production structures. This objective was sub-divided into three intermediate objectives:

- A. Assemble and review all available satellite imagery of pack ice intrusion in the Chukchi Sea for the summer months.
- B. Analyze the location of the pack ice region for the years of available imagery and synthesize maps of expected ice edge location from these data.
- C. Develop probability contour plots of the extent of summertime intrusion of the Chukchi Sea.

These objectives have been addressed as follows:

Objective A: The Geophysical Institute has compiled an extensive archive of Landsat and NOAA imagery of Alaska and nearby waters covering the period starting when these data became available to the present. This archive was utilized to compile a data set containing summertime Chukchi Sea pack ice edge locations for the years 1972 to the present. Ultimately this data set will be used to provide descriptive accounts of specific summertime pack ice incursions in the Chukchi Sea. However, first the important incursion event must be identified by means of a systematic analysis of the data set. (Described below)

Objective B: Calls for the construction of a computer-based geographical information system to facilitate compilation of maps derived from the basic data set. As part of this objective, a set of expected ice edge location maps is to be produced.

In order to construct a geographical information data base, it is necessary to obtain data in geographically correct coordinates. Unfortunately, the satellite imagery covering the widest area and

available on a daily basis (the NOAA AVHRR imagery) is produced by a wide-angle imaging system and the resulting imagery is not geographically rectified. However, the Joint Ice Center, operated by the U.S. Navy in conjunction with NOAA does produce rectified maps of world-wide ice conditions on a weekly basis using the AVHRR imagery and information from other data sets including aerial reconnaissances and ship reports. We have worked closely with the Joint Ice Center during the past two years and have found their methodology for rectifying sea ice data to be satisfactory for the purposes of this study. Therefore we have digitized the rectified ice maps and placed that data set into the geographic data base. Twelve years' data were available.

This data base has been used to generate a set of 27 weekly digital maps spanning the period from the first week in June (when the Chukchi Sea first begins to open) to the first week in December (when the Chukchi Sea is ice covered). The maps display the maximum, minimum and median ice extent in the Chukchi Sea on a weekly basis over the period described above. However those digital maps must be re-drafted to a standard coastline map base before presentation because of the "blocky" nature of the coast on the digital map. This work is in progress. While these maps will be useful toward developing a picture of the Chukchi Sea ice conditions, they are not the principal data product to be produced. This product is part of that described under objective C.

Objective C. This objective calls for three principal data products:

1. The overall probability of pack ice being encountered at specific locations as a function of time. When considering

ice conditions to be encountered at a specific location, it is not convenient (nor very useful) to look through a set of 27 maps to determine ice probabilities for that location. What is required here is a plot for that location showing the probability that it will be within the pack ice edge as a function of time. For this purpose an array of 67 points throughout the study area have been chosen for which such plots are being prepared. This work is currently underway. It utilizes a simple program accessing the geographically-based data set compiled under objective A.

2. The minimum, maximum and average duration of the ice free period (and standard deviation from the average ice free period) for specific locations in the Chukchi Sea. This product will consist of a table compiled from the geographically-based data set generated under objective A. The above-mentioned values will be listed for each of the 67 locations described above. This objective will be addressed after the completion of the data product described in (1) above.
3. The probabilities of mid-season pack ice incursion during normally ice-free periods at various Chukchi Sea locations. Clearly this parameter will be a function of time. For instance, if we take the normally ice free period to be defined by the dates by which the probability of ice free conditions reaches 75%, the probability of a pack ice "incursion" would simply be the statistical pack ice probability after that date. This is simply little more than

a re-definition of the data product described in paragraph 1 above. What we really need to address here is the probability that once the pack ice has been apparently removed for the season, it will return. Hence we are speaking of a conditional probability. These calculations will be based on sequential analysis of each year's ice behavior for each location. (This will be a derived product based on the intermediate data set generated in the preparation of product #1 above.)

In general, the work being performed under this section is on schedule and no problems are anticipated that would prevent delivery of our final report on schedule.

3. Spray Ice Adhesion to Offshore Structure Coatings

During the first quarter, a standard steel cylindrical substrate was chosen, 1.67 inches in diameter and 30 inches in length. Assuming a test region of length 24 inches, a ratio of length to diameter (l/d) of 14.37 is available, which will justify the neglect of end effects at the bottom of the sample. A contact area of 125.92 square inches is expected, leading to an estimated torque range at failure from about 87 to 350 lb.-ft. This is based upon 10-40 psi shear strength and determines the range of the equipment to be designed for the measurement. Actually, provision will be made to apply torques ranging from zero up to about 350 lb.-ft, in anticipation of weak bond strengths for some coatings. A precisely-reamed pin connection at the top of the

cylinder was provided for coupling to the loading apparatus, which is to be designed.

Cylindrical substrates, as described above, were fabricated, and three such cylinders were coated with the icebreaker epoxy coating used throughout the world, Inerta 160, through the courtesy of Teknos-Maalit Oy, Helsinki, the manufacturer. Two more cylinders were coated with Teflon tape in a spiral pattern, and two were coated with a common alkyd industrial enamel #14212, by Glidden Coatings and Resins, Cleveland, Ohio. Two cylinders were left uncoated. It was further recognized that the formation of spray ice on the substrate would vary with different weather conditions, and that the adhesion would depend on the physical details at the interface of the ice and the surface. To examine that closely, a transparent split cylinder was fabricated from plexiglass, of approximately the size of the steel cylinders.

A mounting fixture was also constructed for holding all of these cylinders in a vertical orientation in a remote beach location subject to spray ice accumulation at St. Paul Island, Alaska. Arrangements were made with the Tanadgusix Corporation at St. Paul Island to assist in the deployment and retrieval of the cylindrical substrates. A field trip was scheduled for the second quarter to collect the initial set of spray ice samples.

In connection with another project, a trip to Helsinki was made and contact with Prof. Lainianen at the Geophysics Institute, University of Helsinki, resulted in a useful information interchange and a possibility of further cooperation. He forms spray ice in a wind tunnel with controlled wind velocity and spray injection rates, although ambient air temperature prevails.

Results of the field trip will appear in the next quarterly report.

III. PLANS FOR NEXT QUARTER

1. Ice Islands

Analysis of the trajectory of the ice island which is presently tagged will begin. This will involve the examination of surface and 850 mbar pressure charts of the Northern hemisphere to calculate local geostrophic winds at the ice island during the two types of movement episodes. This will be the subject of a M.S. thesis in Geophysics by M. Yan, and is expected to require about one year to be thoroughly completed.

Arrangements will be made for the Argos buoy to be constructed for the second ice island, (Figures II-12 to II-14). Deployment is scheduled for the third quarter. NOAA Satellite imagery of the northern coast of Ellesmere Island, although low in resolution, will be ordered and examined for supplemental information on possible large ice island formation, and ice shelf boundary information. Aerial photography of the north coast of Greenland will be reviewed as well. Sources of information also to be included are the detailed surface traverse logbooks of Mr. Harold Serson, who covered the region each year for two decades.

The aim of this part of the project is to assemble all possible information on ice island generation, to acquire trajectories and relate them to weather conditions, and to develop a model to predict the probability of encounter of an ice island with an offshore structure in

the Alaskan Beaufort and Chukchi Seas. Significant progress is expected this year in these directions.

2. Chukchi Sea Pack Ice Edge Statistics

1. Place the statistical ice edge data on line-drawn geographic maps.
2. Construct ice edge probability plots for the array of 67 analysis points located throughout the study area.

3. Spray Ice Adhesion to Offshore Structure Coated Surfaces

A field trip to St. Paul Island will be made, and spray ice samples collected and examined. Possible improvements in fixturing will be developed for field sampling. Analysis of ice from this field trip will begin. A more detailed plan of cooperative research with Prof. Laininen will be composed. Designs of the loading apparatus will be initiated.

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Figure I-1-1.

Map of Ward Hunt Ice Shelf and vicinity to show calving of shelf and position of new ice islands on 13 June 1962 (after Hattersley-Smith, 1963).

(10,000 ft.)

Figure I-1-2 Aerial photograph of ice island fragments.

Figure II-2 Thick ice floe ("Beta") at $82^{\circ}36.8'N$, $85^{\circ}50.1'W$, on
October 19, 1983.

Figure II-3 Cracks in pack ice around floe "Beta".

Figure II-4 Cracks in pack ice around floe "Beta".

Figure II-5 Cracks in pack ice around floe "Beta".

Figure II-6 View of "Beta" from $82^{\circ}38.4'N$, $85^{\circ}54'W$.

Figure II-7 Ice island "Gamma" with one sharply-defined edge.

Figure II-8 Ice island "Gamma" with one sharply-defined edge.

Figure II-9 Opposite edge of "Gamma" tapering to normal pack ice thickness.

Figure II-10 Opposite edge of "Gamma" tapering to normal pack ice thickness.

Figure II-11 Extreme tip of "Gamma".

Figure II-12 Ice island "Delta" with distinct freeboard and three surface undulations.

Figure II-13 Edges of ice island "Delta".

Figure II-14 Edges of ice island "Delta".

Figure II-15 Edges of ice island "Delta".

Figure II-16 Edges of ice island "Delta".

Figure II-17 Very old multi-year ice floe in same region as ice island "Delta".

Figure II-18 Very old multi-year ice floe in same region as ice island "Delta".

Figure II-19. Map dividing Ellesmere Island Coast into regions for Ice Shelf Study.

Figure II-20 Eastern part of mouth of Yelverton Bay on October 19, 1983.

Figure II-21 Shoreline at eastern boundary of Yelverton Bay on
October 19, 1983.

Figure II-22 Mouth of Yelverton Bay, October 19, 1983.

Figure II-23 Combined photo (11-21 and 11-22) of mouth of Yelverton Bay,
October 19, 1983.

Figure II-24 Thick ice shelf in unnamed Inlet, October 19, 1983.

Figure II-25 Thick ice shelf in unnamed Inlet, October 19, 1983.

Figure II-26 Combined photo of ice shelf in unnamed Inlet, with rolling top surface

Figure II-27 Ice Rise at Cape Evans, October 19, 1983.

Figure II-28 Ice at Cape Egerton, October 19, 1983, showing edge of Milne Ice Shelf.

Figure II-29 Smooth ice shelf at Cape Egerton, October 19, 1983.

Figure II-30 Ayles Ice Shelf, smooth surface, October 19, 1983.

Figure II-31 Ayles Ice Shelf, October 19, 1983.

Figure II-32 Ayles Ice Shelf, October 19, 1983.

Figure II-33 Ice at Cape Fanshawe Martin, October 19, 1983.

Figure II-34 Ice shelf extending towards Bromley Island, October 19, 1983

Figure II-35 McClintock Ice Shelf, smooth and flat, October 19, 1983.

Figure II-36 Westernmost part of Ward Hunt Ice Shelf, October 19, 1983.

Figure II-37 Rolling surface topography of Ward Hunt Ice Shelf,
October 19, 1983.

Figure II-38 Camp maintained on Ward Hunt Ice Shelf by Polar Continental Shelf Project, looking northward, October 19, 1983.

Figure II-39 Camp maintained on Ward Hunt Ice Shelf, looking southward, October 19, 1983.

Figure II-40 Ward Hunt Ice Shelf outer boundary, October 19, 1983.

Figure II-41 Ward Hunt Ice Shelf west of Ward Hunt Island,
October 19, 1983.

Figure II-42 Ice rise at Ward Hunt Island, October 19, 1983.

Figure II-43 Re-entrant edge region of Ward Hunt Ice Shelf showing region of recent (1982) ice island generation; photo taken October 19, 1983.

Figure II-44 Sea ice and outer edge of Ward Hunt Ice Shelf showing Cape Albert Edward, October 19, 1983.

Figure II-45 Outer edge of Ward Hunt Ice Shelf, at mouth of Disraeli Fjord, October 19, 1983.

Figure II-46 Ward Hunt Ice Shelf between Cape Albert Edward and Ward Hunt Island, October 19, 1983.

Figure II-47 Ward Hunt Ice Shelf between Cape Albert Edward and Ward Hunt Island, October 19, 1983.

Figure II-48 Ward Hunt Ice Shelf between Cape Albert Edward and Ward Hunt Island, October 19, 1983.

Figure II-49 Ward Hunt Ice Shelf between Cape Albert Edward and Ward Hunt Island, October 19, 1983.

Figure II-50 Ward Hunt Ice Shelf between Cape Albert Edward and Ward Hunt Island, October 19, 1983.

Figure II-51 Ward Hunt Ice Shelf at mouth of Disraeli Fjord,
October 19, 1983.

Figure II-52 Change in periodicity of upper surface of Ward Hunt Ice Shelf in Disraeli Fjord, October 19, 1983.

Figure II-53 Ward Hunt Ice Shelf near Marvin Islands, October 19, 1983.

Figure II-54 Canded upper surface of ice shelf in Disraeli Fjord,
October 19, 1983.

Figure II-55 Canded upper surface of ice shelf in Disraeli Fjord,
October 19, 1983.

Figure II-56 Canded upper surface of ice shelf in Disraeli Fjord,
October 19, 1983.

Figure II-57 Canded upper surface of ice shelf in Disraeli Fjord,
October 19, 1983.

Figure II-58 Canded upper surface of ice shelf in Disraeli Fjord,
October 19, 1983.

Figure II-59 Smooth ice within Disraeli Fjord, October 19, 1983.

Figure II-60 Smooth ice within Disraeli Fjord, October 19, 1983.

Figure II-61 Smooth ice within Disraeli Fjord, October 19, 1983.

Figure II-62 Smooth ice within Disraeli Fjord, October 19, 1983.

Figure II-63 Smooth ice within Disraeli Fjord, October 19, 1983.

Figure II-64 Smooth ice near end of Disraeli Fjord, October 19, 1983.

Figure II-65 Glacier on east side of Disraeli Fjord, October 19, 1983.

Figure II-66 Eastern edge of Ward Hunt Ice Shelf, at Cape Albert Edward,
October 19, 1983.

Figure II-67 Ice shelf east of Cape Albert Edward, October 19, 1983.

Figure II-68 Coastline free of ice shelf east of Ward Hunt Ice Shelf,
October 19, 1983.

Figure II-69 Shelf ice in Markham Fjord, October 19, 1983.

Figure II-70 Shelf ice in Markham Fjord, October 19, 1983.

Figure II-71 Shelf ice in Markham Fjord, October 19, 1983.

Figure II-72 Flat ice shelf from Cape Aldrich to Good Point,
October 19, 1983.

Figure II-73 Flat ice shelf from Cape Aldrich to Good Point,
October 19, 1983.

Figure II-74 Smooth ice from Good Point to Cape Colan,
October 19, 1983.

Figure II-75 Smooth ice from Good Point to Cape Colan,
October 19, 1983.

Figure II-76 Undulating surface shelf ice from Stuckberry Point to Cape Colan, west of Clements Markham Inlet, October 19, 1983.

Figure II-77 Undulating surface shelf ice from Stuckberry Point to Cape Colan, west of Clements Markham Inlet, October 19, 1983.

Figure II-78 Undulating surface shelf ice from Stuckberry Point to Cape Colan, west of Clements Markham Inlet, October 19, 1983.

Figure II-79 Undulating surface shelf ice from Stuckberry Point to Cape Colan, west of Clements Markham Inlet, October 19, 1983.

Figure II-80 Undulating surface shelf ice from Stuckberry Point to Cape Colan, west of Clements Markham Inlet, October 19, 1983.

Figure II-81 Deformed ice rubble at the mouth of Clements Markham Inlet,
October 19, 1983.

Figure II-82 Deformed ice rubble at the mouth of Clements Markham Inlet,
October 19, 1983.

Figure II-83 Smooth, featureless ice of undertermined age and thickness
in Clements Markham Inlet, October 19, 1983

Figure II-84 Smooth, featureless ice of undertermined age and thickness
in Clements Markham Inlet, October 19, 1983

Figure II-85 Smooth, featureless ice of undetermined age and thickness
in Clements Markham Inlet, October 19, 1983

Figure II-86 Smooth, featureless ice of undetermined age and thickness
in Clements Markham Inlet, October 19, 1983

Figure II-87 Smooth, featureless ice of undetermined age and thickness
in Clements Markham Inlet, October 19, 1983

Figure II-88 Smooth, featureless ice of undetermined age and thickness
in Clements Markham Inlet, October 19, 1983

Figure II-89 Smooth, featureless ice of undetermined age and thickness
in Clements Markham Inlet, October 19, 1983

Figure II-90 Smooth, featureless ice of undetermined age and thickness
in Clements Markham Inlet, October 19, 1983

Figure II-91 Smooth, featureless ice of undetermined age and thickness
in Clements Markham Inlet, October 19, 1983

Figure II-92. Trajectory of the Ice Island instrumented by Dr. George Hobson, August 13-December 13, 1983.