9.0 MONITORING

Monitoring of ice islands is required to achieve a number of objectives:

- Provide information on island properties to verify compliance with design assumptions during construction. The contractor also requires this information to resolve scheduling and productivity issues;

- Allow acceptance of the island on completion prior to use as a drilling platform to ensure it meets the design specifications;

- Provide data on the performance of the island during drilling to establish whether it is performing as expected, and whether to initiate maintenance or repair operations.

The installation and performance of the monitoring system must address each of these requirements at the appropriate stage of the island life cycle.

9.1 Construction Verification

The important parameters that are stated as part of the design of an ice island, and must be verified during construction are:

- Geometry – the freeboard and diameter of the grounded island are critical to ensuring global stability of the completed island. Build-up stakes are the usual method of allowing the island geometry to be measured, with daily surveying during construction. A grid is usually established over the area of the island, which includes a number of reference stakes on the natural ice outside of the island footprint. A suitable spacing must be established to allow accurate profiling, but not too close to impede movement of the construction equipment.

- Density – The density of the spray ice is specified in the design to ensure sufficient bearing load on the seabed, and to provide capacity to support surface loads. The density is measured by taking core samples of ice at known depths during construction. Since the density can change with time as the spray ice cures, the samples taken during construction provide an indication of construction quality. The surface of the islands can be formed to provide a denser crust by flooding and curing to allow construction traffic.

- Ice temperature – Since ice strength is a function of temperature, it is important to maintain the ice at a cold enough temperature throughout its depth. Control of temperature during construction is used to control the island core temperature throughout its operating life, and is usually obtained by applying layers of ice and allowing time to cure and cool prior to applying the next layer. Monitoring of temperature allows the lift and cure process to be optimized according to ambient temperature. Temperature is monitored by installing thermistor strings as the island is constructed. These may be connected to dataloggers, which automatically read and record temperature. Alternatively, they may be read manually.

- Ambient environmental conditions – this is required by the contractor to allow efficient construction of the island. The critical parameters that affect production rates are air temperature and wind speed. Through experience of constructing islands, contractors have developed operational guidelines for spraying procedures as a function of these environmental conditions.

9.2 Post Construction Acceptance

The data collected during construction provides an indication that the process is producing an acceptable quality of product. On completion of the construction process, the island must be approved for use as a drilling platform, and as well as reviewing the construction monitoring data, further tests can be undertaken to provide the data on which to base this decision. These additional tests may consist of:

- As-built geometry – this is confirmed by undertaking a final survey of the island.

- Strength Tests – the most common method of establishing strength is through in-situ testing using a cone penetrometer test (CPT). The CPT is advanced through the ice and into the seabed whilst measuring force at its tip. This identifies any voids in the island and whether the island has grounded and is in good contact with the seabed. Further, correlations have been developed to allow the strength of the ice to be determined from measured CPT force. Cores can also be taken by drilling through the island, and testing could include temperature, density, salinity and confined or unconfined compression tests to confirm that the ice meets design specifications. The use of flat jacks and borehole jacks also provides data on the strength and stiffness of the spray ice.

9.3 Performance Monitoring

The behaviour of the ice island during operation of the drilling rig is required to ensure that it is performing as expected. Measurement of appropriate parameters provides an early warning of any undesirable effects, and allows time to undertake modifications to minimize interruption to drilling activities. Suitable monitoring for performance of the island includes:

- Natural ice thickness and movement – the movement of land-fast ice occurs as a result of wind, pack-ice movement or thermal events. The use of survey stakes and wireline movement stations, which measure differential movement between locations, would provide information of ice movement. This is suitable for measuring the movement of natural ice, where stations are not likely to be disturbed by drilling activities. Ice thickness can be measured by drilling through it and either measuring thickness directly or measuring freeboard, from which total thickness can be inferred.

- Island movement – as load is transferred from a moving natural ice sheet to the island, some island displacement is possible. The use of slope inclinometers installed through the island and into the seabed would provide profiles of horizontal movement at various depths through the island. This data would provide information on any internal deformation within the island, as well as sliding along the seabed. Interpolation between inclinometer locations also allows inference of island distortion during loading events.

- Island settlement – The use of survey methods allow surface settlement of the island to be monitored. This may be settlement of the entire island due to creep from overburden, or settlement of facilities where load is concentrated. Further, ablation of the island surface will occur during the latter part of the drilling season as temperatures start to exceed 0^{o}C. For a grounded island, this will be measured as a reduction of surface level by survey.

- Ice temperature – it is important to maintain the ice temperature below the design value to maintain island integrity. The risk of warming the ice comes from the various heat sources during drilling, particularly around the cellar as heat is transferred from the conductor. Other locations of heat transfer come from accommodation buildings and generators as well as increased absorbtion of the dirtied ice surface. Temperature monitoring is achieved using thermsitor strings placed horizontally and vertically in the ice during construction.

- Ice forces – A number of islands and protection structures have incorporated ice load panels at their perimeters to measure load events. This information can be useful in establishing the level of loads being imposed on the island in comparison with design assumptions. In practice, there are a number of challenges in obtaining reliable data and undertaking interpretation from ice pressure panels, including the effects of strain incompatibility between the sensor and surrounding ice, thermal response and inclined loading onto the panels.

The level of instrumentation and monitoring for any particular ice island is a function of level of confidence in the design assumptions and previous experience of construction and operation in the region. The first islands to be constructed utilized methods of which no previous experience existed, and data was collected to allow back-analysis of performance behaviour of the structures. As experience and confidence improves, less data is usually required as processes become better defined. The level of redundancy of a monitoring system can also be reduced as reliability of the equipment improves with experience.

10.0 MAINTENANCE

The use of ice islands has to date been limited to temporary drilling pads or protection structures. However, adequate maintenance procedures must be performed to ensure that performance specifications are met throughout the design life of the structure. This is particularly important during the latter part of the winter season as temperatures increase and deterioration of the ice begins. The appropriate use of monitoring strategies and preventative maintenance can be particularly beneficial in extending the useful life of the structure at this time.

10.1 General Maintenance

Temperature control of the island is the basis for maintaining structural integrity and reducing risk to the facilities supported on it. All heat sources should be insulated from the ice or incorporate an air gap, with particular attention to well conductors, drilling mud, power generators and accommodation units. The island temperature in these areas is usually monitored using thermistor strings embedded in the ice, and a maximum target temperature of $-5^{o}C$ is often specified to maintain adequate ice strength. The well cellar and rig mat area is often actively cooled using a brine or glycol refrigerated circulation system, as utilized at Nipterk, Cape Alison and Karluk platforms and shown schematically in Figure 10.1. The risk of spillage of liquids such as drilling muds or fuel must also be mitigated with the use of strict handling procedures and containment devices such as drip trays.

Cracks have been observed within islands during construction at touch down on the seabed. These cracks are usually filled at the surface as ice build-up continues, although deeper sections may never be fully filled. These cracks do not often reopen to the surface of the island once it becomes grounded and stable, but it is important that they do not create a path for contaminants or thermal erosion of the island core. The location of previously observed cracks should be monitored to ensure that any crack deterioration be filled.

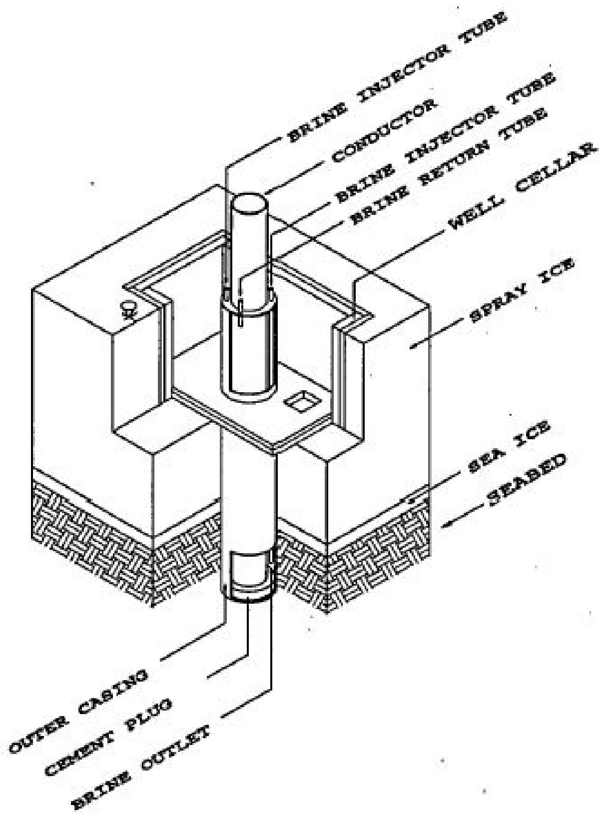


Figure 10.1: Typical Refrigerated Well Cellar (St Lawrence 1992)

10.2 Extended Operations

Surface ablation is a concern as temperatures increase in the spring. Loss of ice due to melting of the island occurs due to atmospheric effects as the air temperature rises above 0^oC, and oceanographic effects as the edge of the island is exposed to wave and current action.

Atmospheric ablation is strongly influenced at temperatures close to 0^oC by the presence of surface debris, whereby there is a balance between increased heat absorption and improved insulation as debris thickness increases. Melting effects from darkening of the surface can be overcome however by placing thin layers of fresh ice or snow on the island at regular intervals through its operational life to maintain reflection of solar radiation. Under typical Beaufort Sea conditions, surface ablation can start in April, and becomes significant by mid May. Ablation rates of up to 2m per month have been observed in June and July (Weaver et al, 1991).

The development of open water around the island as the natural ice cover is reduced leads to significant melting of the island perimeter through thermal and mechanical erosion. Thermal action occurs when high local water velocities result in increased heat transfer between the ice edge and the surrounding seawater. This leads to undercutting of the above water ice, which in turn fails as a cantilever under gravity due to lack of support.

Breakup of the ice sheet and development of open water around the island in late June leads to rapid erosion of its perimeter and erosion rates of up to 30m per day have been noted (Poplin 1990).

The effects of surface ablation and edge erosion can be interdependent, and in particular, edge failure can occur as a result of loss of freeboard. As surface melting takes place, the island can become locally buoyant and induced bending stresses can lead to the formation of cracks which eventually allows sections to separate and float away from the island.

A project was undertaken at the Nipterk ice island to investigate methods of reducing surface ablation and edge erosion, and is reported in detail in Poplin (1990). A range of protective measures were trialed at the end of drilling activities and the rate of erosion compared. This included both surface covering material such as gravel, sawdust and rig mats, and protection from wave action such as tarpaulins and nets. The main conclusions to note include:

- Ablation of clean spray ice starts when air temperatures rise consistently above 0^{o}C, but would start earlier for a soiled surface due to reduced albedo effect. However, once the surface debris exceeds a critical thickness, the insulating value overcomes the heat absorption rate and ablation reduces. This critical thickness is thought to be of the order of 5 to 20mm.

- Sawdust was an effective material to reduce ablation rates, and a thickness of as little as 10mm demonstrated benefits. Wood and gravel required thicker covering to achieve the same results.

- The use of insulated and uninsulated tarpaulins provided some protection, but was not as effective as sawdust or other materials.

- It was suggested that the use of stockpiled drilling mud spread over the surface of the island could provide a cost effective solution to slow surface melt rates, subject to environmental concerns being addressed.

- Edge erosion became significant as soon as the natural ice sheet started to breakup, allowing the thermal and mechanical effects of open water to impact directly onto the island.

- The use of impermeable sheets placed at the edge of the island reduced erosion rates considerably. The use of nets to prevent calving was less successful.

The recovery of the island protection systems once the island has been abandoned was identified as an issue, and a salvage operation was necessary to ensure that the tarpaulins and nets did not provide a hazard to shipping or wildlife. Details of the surface ablation protection systems, comparative melt rates and edge erosion rates are given in Figures 10.2 to 10.5.

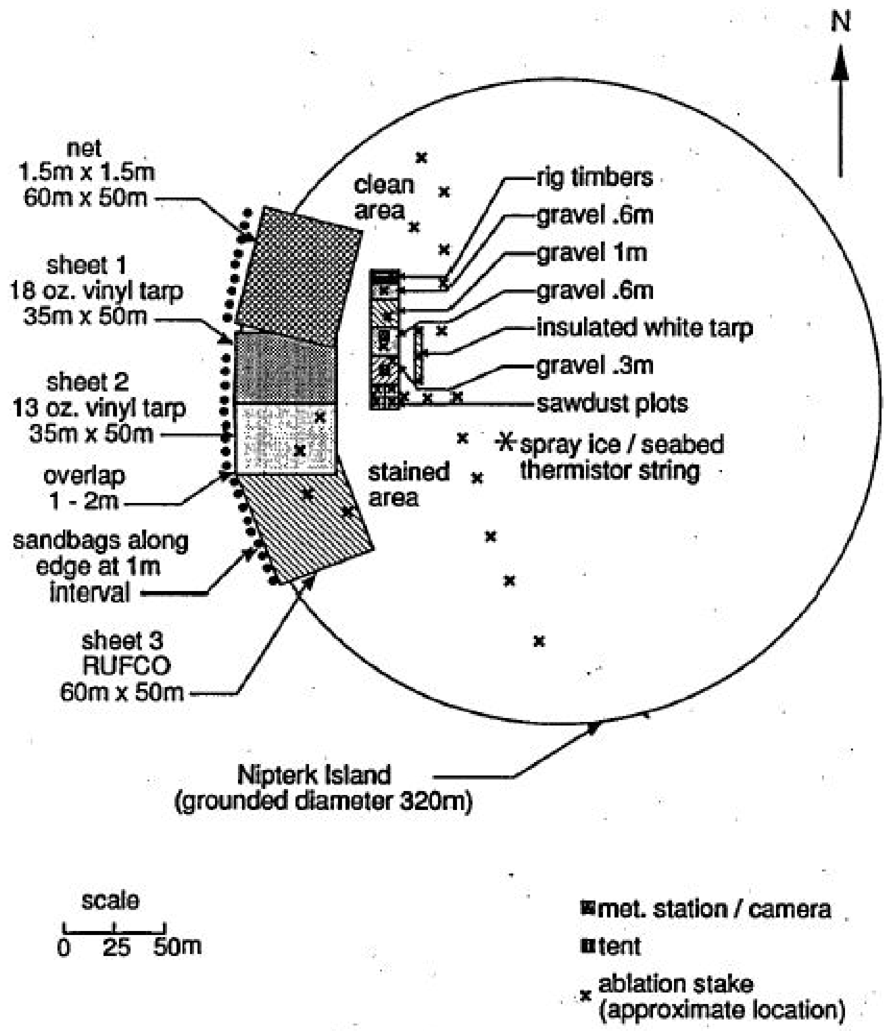


Figure 10.2: Experimental Areas of Ablation Protection on Nipterk Island (Poplin 1990)

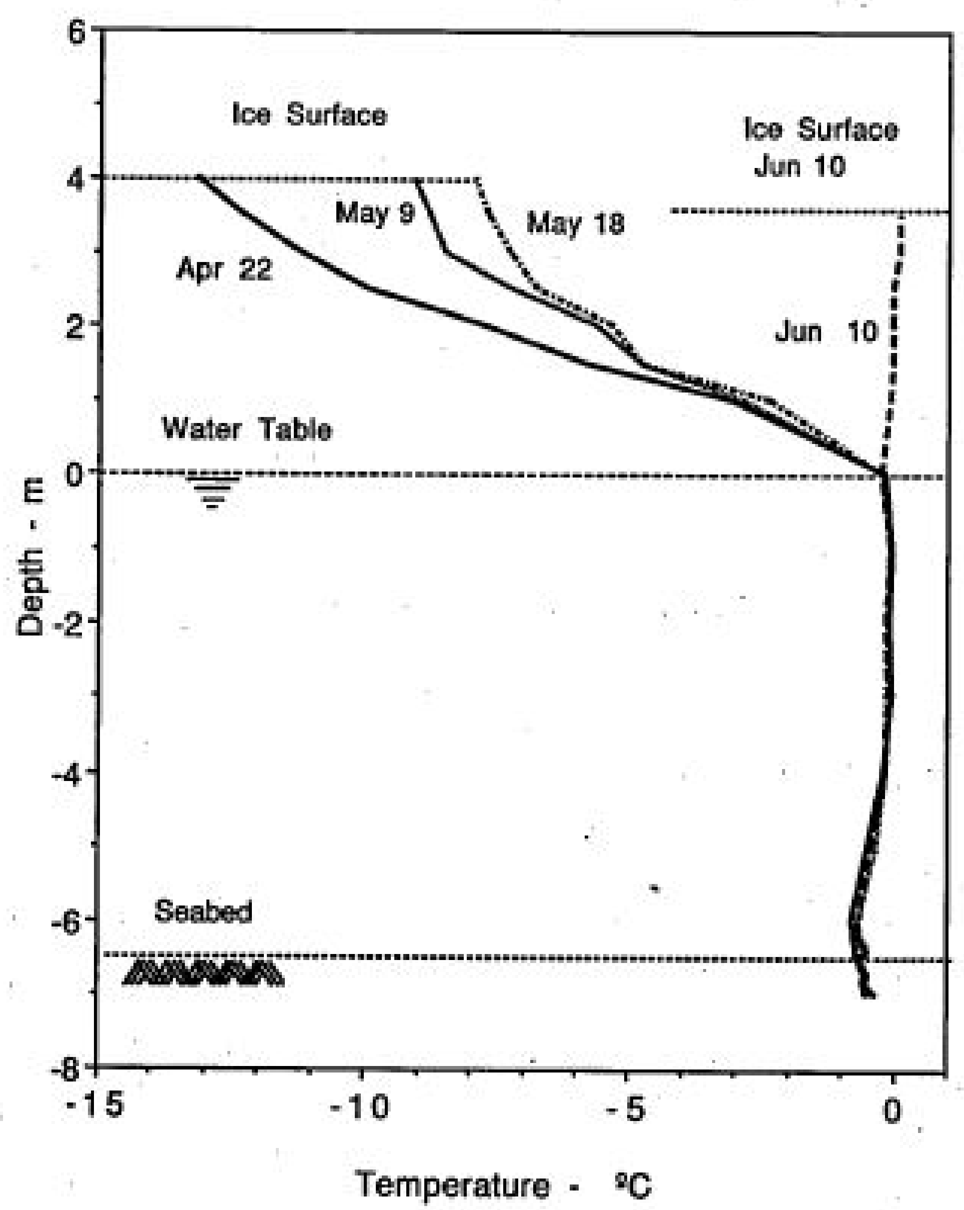


Figure 10.3: Measured Temperature Profile at Nipterk (Poplin 1990)

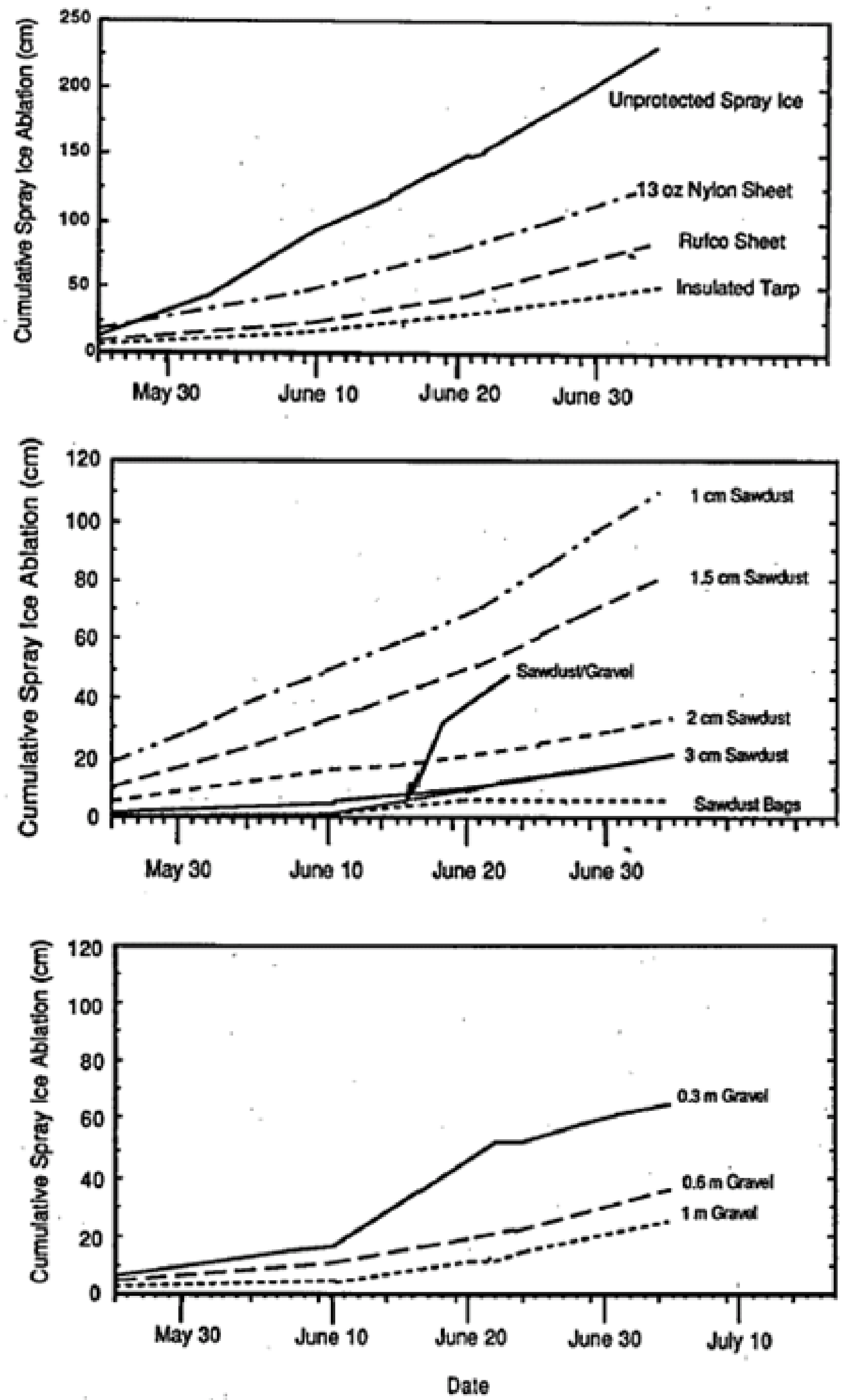
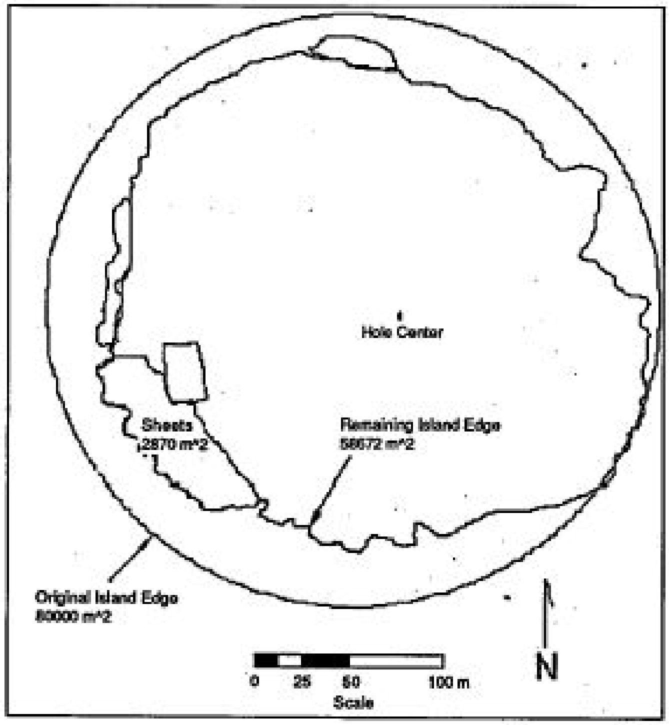


Figure 10.4: Measured Ablation Rates from Various Protective Materials (Poplin 1990)



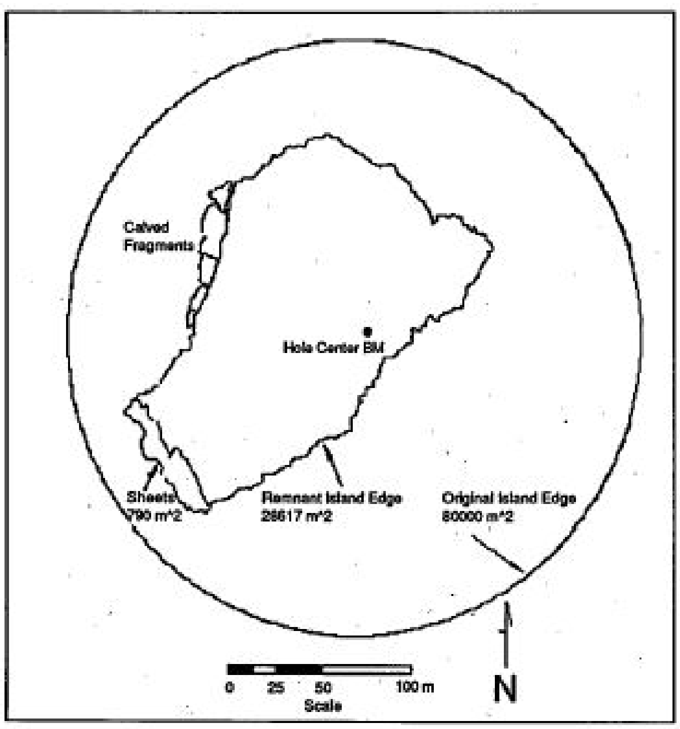


Figure 10.5: Measured Edge Erosion Between July 5th and July 8th (Poplin 1990)

The results of the Nipterk experiment suggested that protection of the island surface and perimeter to allow extended operations into the open-water season is potentially feasible. The method of demobilization of the drill rig and associated equipment would have to be altered to allow transfer to a marine transportation system.

Experience obtained from construction and operation of port structures in Alaska using spray ice has also provided valuable information on improving trafficability and extended season working as temperatures rise in spring. Observations made at two sites in Nome and Red Dog, Alaska (Poplin 1990) generally confirm the points made above relating to the rate of ablation of contaminated (soiled) ice surface. It was further noted that melt rates were accelerated where contaminants did not cover the surface completely, but reduced somewhat when the entire surface was covered. Surface hardness and wear resistant to traffic was improved considerably by adding a layer of gravel and allowing it to freeze in place. A thickness of 300mm was used at these sites, which allowed intensive traffic use immediately without the usual curing time associated with ice road construction. This method also allowed the structure to be used with almost no maintenance during the two month operation. This could have implications on the design of ice roads that are needed to service offshore ice islands.

A study of the deterioration of the Exxon Experimental Ice Island was performed by the United States Geological Survey and reported by Reimnitz et al (1982). The study focused on the erosion features at the edge of the island during the open water season. The island was located near the mouth of the Sagavanirktok River and was strongly influenced by the warm water discharge which produced an upper layer of lower salinity, approximately 5^{o}C warmer than the underlying oceanic water. The erosion of a notch just below the waterline, followed by calving of the resulting shelf material, confirmed the effect of mechanical and thermal effects of open water, with higher rates of erosion at the side facing the river outflow. Erosion rates were measured at between 2.5 and 5m per day, and the last remnants of the island finally floated away in mid-September. Figure 10.6 shows the eroded shape of the island, clearly demonstrating the undercutting due thermal and mechanical wave action that leads to calving of the unsupported surface edge.

Connolly (1986) developed an analytical model for calculating the effect of surface ablation and edge erosion of an ice island during the summer season. The aim of the exercise was to determine the dimensions required to allow an island to survive a summer season whilst remaining grounded and capable of resisting ice loads during that time. The model accounted for heat flux as a result of solar radiation, long wave radiation, sensible heat, evaporative heat, wave action, forced convection, conduction and latent heat. A simulation was performed, based on a hypothetical island in Harrison Bay, Alaska in 15m water depth, and actual meteorological data from 1984 used to determine energy flux through the season. The results suggested that peak surface ablation rates of 0.25m/day would be expected in the first 2 weeks of June, and a total melt of 20m would occur over the summer. Edge erosion during the open water season occurred at a uniform rate of 5.6m/day, resulting in a total loss of diameter of 336m during the summer.

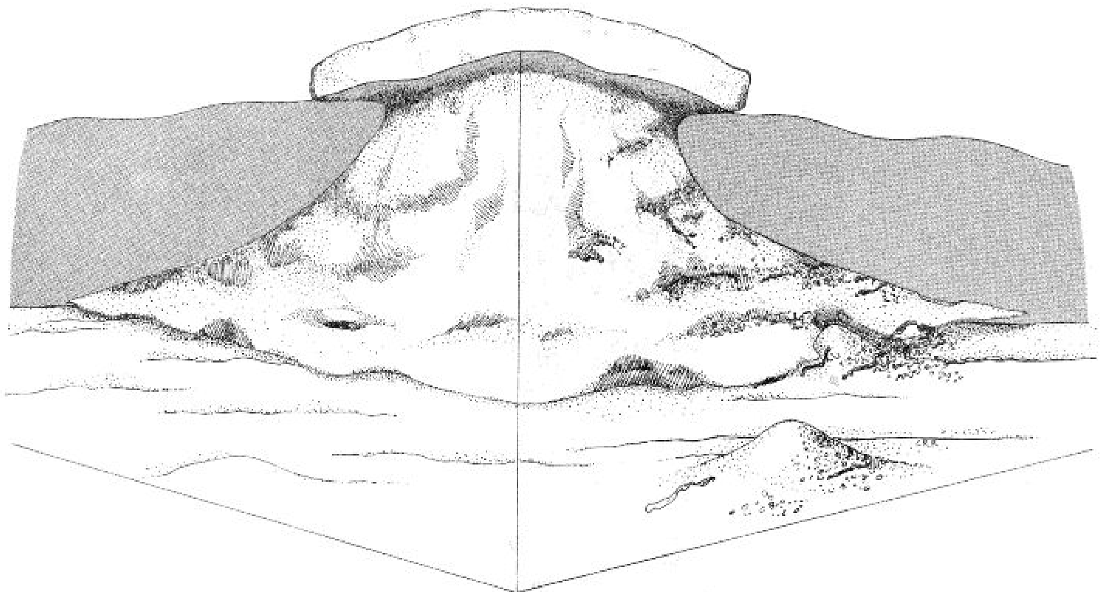


Figure 10.6: Artists Impression of Ice Island Erosion due to Wave Action (Reimnitz et al 1982)

The correlation between island diameter and freeboard dictates its stability to sliding along the seabed as described in Section 7. The results of the modeling performed by Connolly (1986) allowed the minimum island dimensions that would satisfy ice loading conditions at the end of the summer season to be determined, allowing for loss of surface and edge material. A curve was developed that provides the relationship between minimum diameter and freeboard of both design dimensions and resultant end-of-season dimensions. Figure 10.7 presents this data, and indicates that a minimum constructed island dimension of 1000m diameter and 36m freeboard would allow it to survive a summer season for use as a drilling platform the following winter. The required initial size of the island could be lowered considerable by implementing protection of the surface and edge as described above. The analysis neglected the practical considerations regarding construction of such a large structure and the logistics of rig transportation to and from the island, and more rigorous analysis may be warranted.

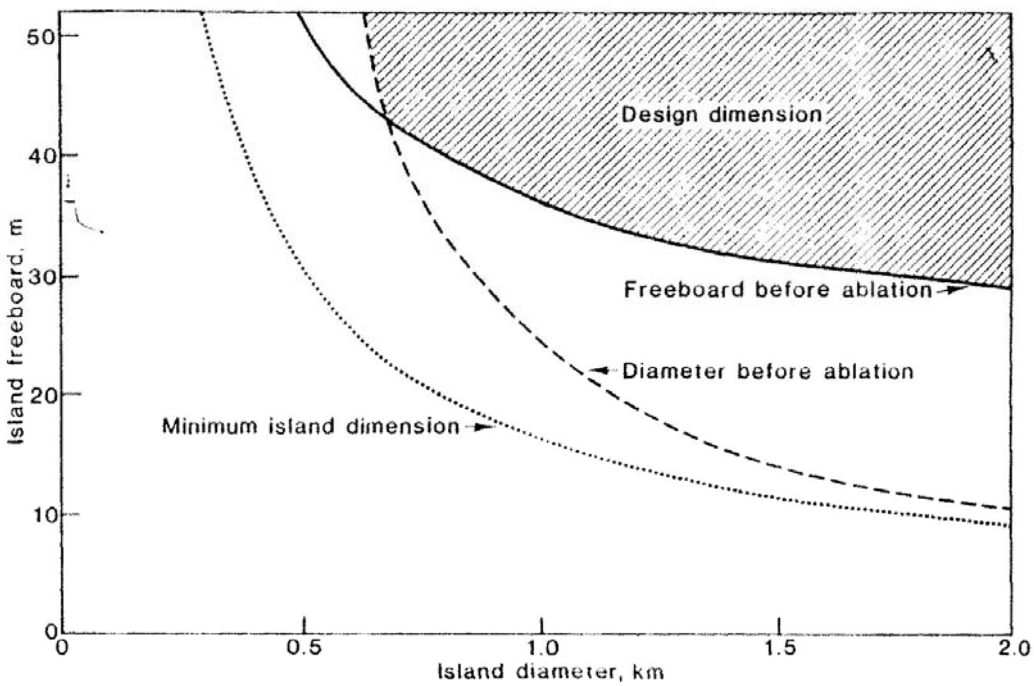


Figure 10.7: Required Dimensions for Multi-year Ice Island Survival (Connolly 1986)

10.3 Operations in Deeper Water

The review of spray ice structures for offshore use to date indicates that they have been constructed using one of two methods; on-ice construction using heli- or road transportable pumping equipment for drill support structures, or off-ice using pumps mounted on ice breakers or structures positioned during the preceding summer open water season. Each of these methods is limited in terms of earliest start date by the presence of ice for supporting equipment or to act as a starting point for spray ice construction.

Weaver et al (1991) evaluated the potential for overcoming the limitations on logistics and construction methodology to allow the construction of spray ice islands in deeper water. Each construction methodology was considered separately to determine their limits of operation.

On-ice construction is limited by the presence of stable landfast ice conditions and adequate thickness to support the pumps and associated equipment. These conditions are typically satisfied within 2 weeks of the onset of landfast ice at any given location (Weaver et al 1991). Data for the Canadian Beaufort Sea suggests that there is an 80% probability of experiencing suitable landfast ice for a construction start date of mid-December at 10m water depth and mid-January at 14m water depth as shown in Figure

10.8. A 50% confidence level of forming landfast ice at these depths is obtained in mid-November and early-December respectively. Similarly, the air temperature drops to -20°C around the end of November in both US and Canadian Beaufort Sea as shown in Figures 10.9 and 10.10, which would allow efficient spray ice construction. This suggests that the start of construction is dependent on ice landfast formation rather than adequately cold temperatures at sites situated in excess of 6.5m and 10m water depth for 80% and 50% confidence levels respectively. Data for ice islands constructed off landfast ice have been added to Figure 10.8, in terms of the start date for construction (spraying) as a function of water depth. This shows that in general, the start of construction has been significantly later than the time at which landfast ice would be expected to support the required loads, suggesting that earlier start times are possible. The presence of some grounded multi-year ice floes in shallow areas promotes the formation of stable ice early in the season. However, due to fewer grounded first-year ridges, the landfast ice may be subjected to greater movements during storms. This is a risk that must be considered in both design of the island and drilling operations.

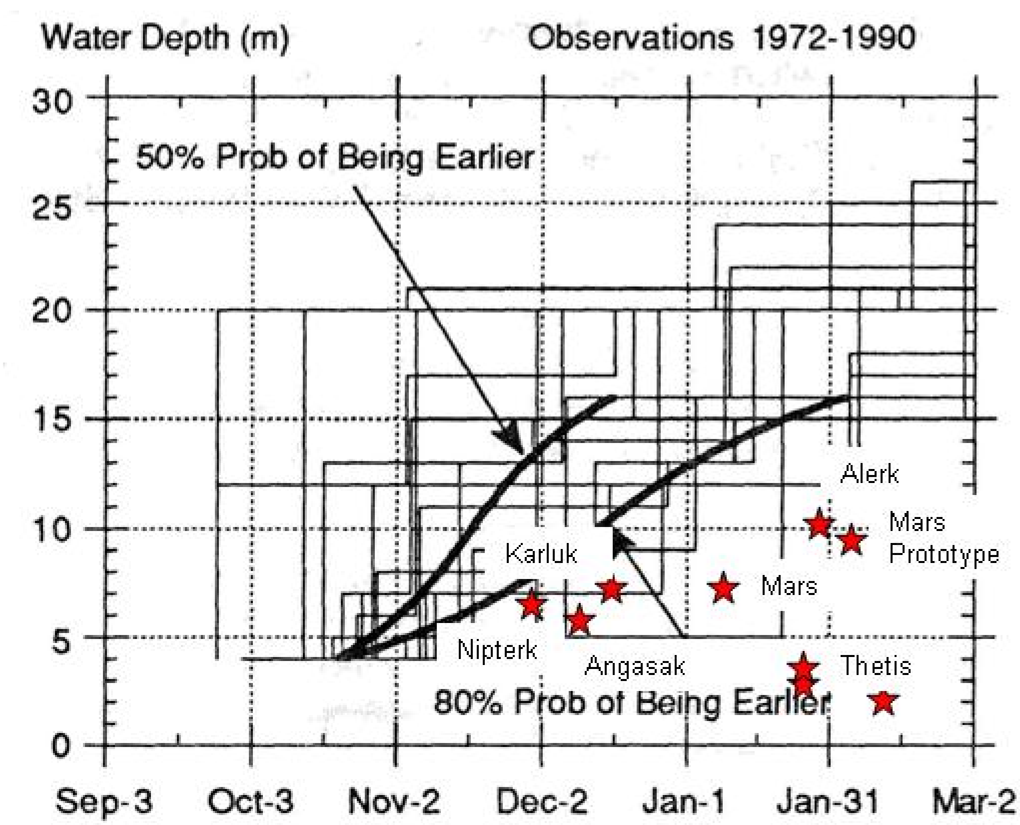


Figure 10.8: Development of Landfast Ice as a Function of Water Depth (Weaver et al, 1991, modified)

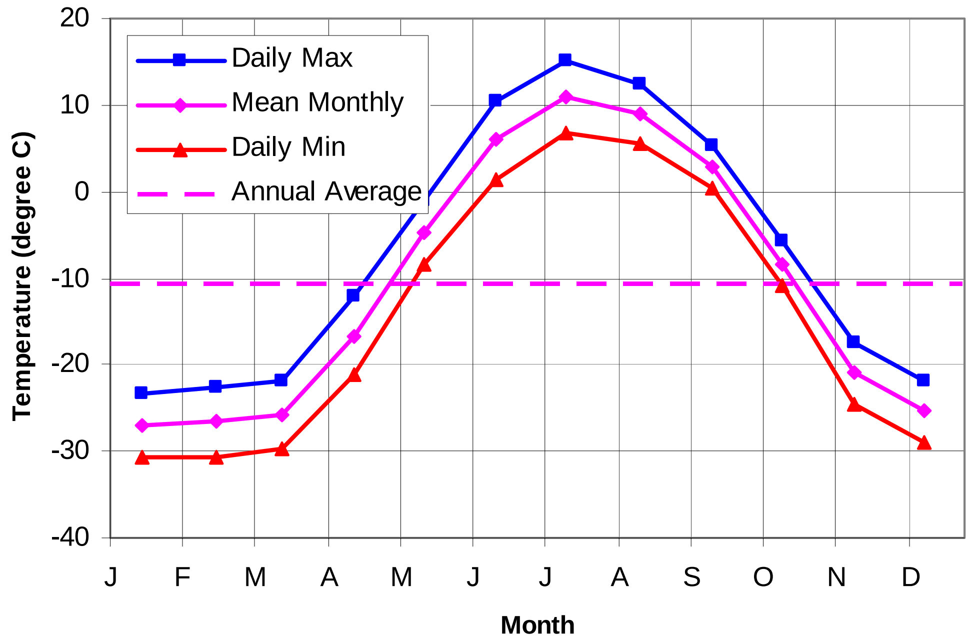


Figure 10.9: Air Temperature for Tuktoyuktuk, Canadian Beaufort Sea 1971-2000 (Environment Canada, 2005)

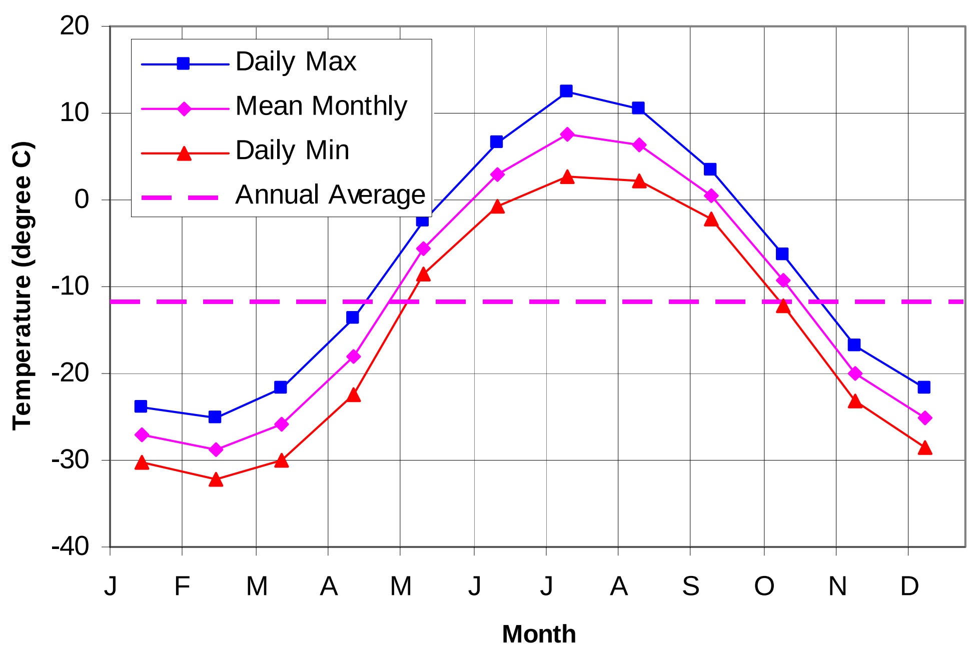


Figure 10.10: Air Temperature for Prudhoe Bay, Alaskan Beaufort Sea 1971-2000 (Alaska Climate Research Center, 2005)

Based on experience to date, operational spray ice islands have been constructed in a period of 20 to 60 days, with an average of 30 days. As construction proceeds into greater water depths, construction time would be expected to increase as a function of the greater material required. Using assumptions with respect to volumetric requirements and attainable production rates, Weaver et al (1991) concluded that it is possible to complete a spray ice island in 10 to 11m of water depth by March 15th in any given year using on-ice techniques and current equipment. Schedule requirements for drilling activities suggests that completion of ice islands are usually required by the first week of February, as discussed later in this section, and so improved construction techniques would be required to meet such a schedule.

One method of improving production rates is through the development of larger pumps with up to 500 l/sec (30m^3/min) capacity. Experience shows that the relationship of volume production rate verses pump capacity is not linear, but closer to an exponential fit (Masterson 2005, personal communication) as a function of longer spray trajectory and exposure of the water droplets to the cold ambient temperature. Figures 10.11 and 10.12 demonstrate this factor based on operational experience. The same trend lines have been presented in each plot to allow comparison at different scales.

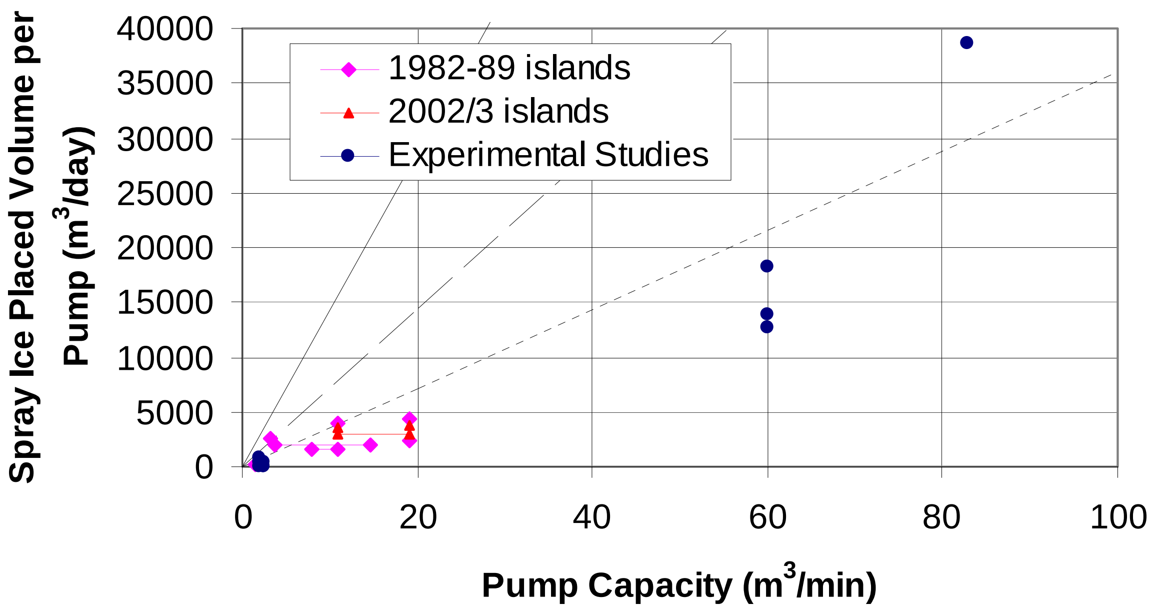


Figure 10.11: Relationship Between Ice Volume and Pump Capacity (All Data)

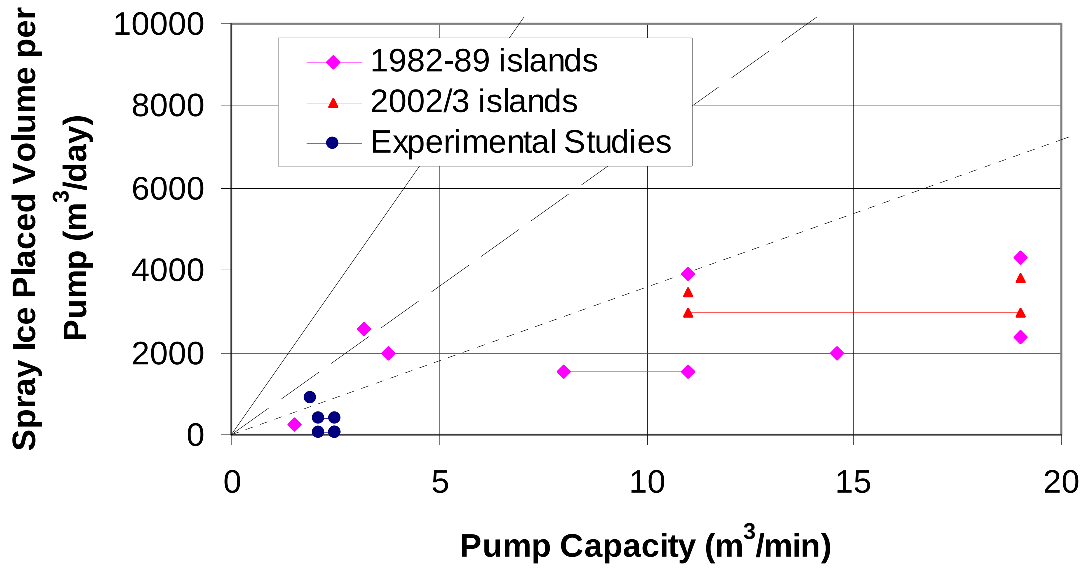


Figure 10.12: Relationship between Ice Volume and Pump Capacity (Smaller Pumps)

Another method of allowing construction of spray ice islands in deeper water would be to consider the use of off-ice techniques. Such systems have been used for the construction of barriers such as at the Sohio experiments (ORourke 1984) and CIDS Antares site (Jahns et al 1986). The potential advantages of this method include the possible use of larger vessel mounted pumps, earlier start dates and lower volume requirements. As discussed above, temperatures reach –20°C, cold enough for efficient spray ice production, by the end of November in the Beaufort Sea. Incursions of multi-year ice could be loaded with spray ice to nucleate a grounded structure. Significant ice movement would be expected between early November and development of landfast conditions in deeper water, which would cause generation of rubble mounds around a grounded structure. The presence of grounded rubble fields would, in turn, reduce the volume of spray ice required for the island. The alternative techniques explored in the O'Rourke (1984) studies also considered the use of off-ice construction techniques to allow spray ice structures to be built in deeper water. The use of floating or grounded barges were also proposed to overcome issues of rig deployment from land, and used similar concepts to those employed with the CIDS protection structures.

Consideration of these factors demonstrated that an ice island could be constructed in 16m water depth by early March (Weaver et al, 1991). Again, completion of ice island construction should be targeted for early February to allow adequate time for drilling. Figure 10.13 shows projected island completion dates from Weaver et al (1991), superimposed with data from actual island completions. Data from off-ice spray ice barriers is included, which generated similar volumes of ice from the CIDS and SSDC structures and the MV Kigoriak vessel. It should be noted, however, that the volume requirement will be significantly increased in deeper water without the use of natural rubble, and so construction times would be increased for structures in these water depths. The plotted data shows that completion dates for on-ice construction compares well between theoretical and actual construction. The use of high capacity, off-ice methods suggest that theoretical values can be significantly bettered in practice.

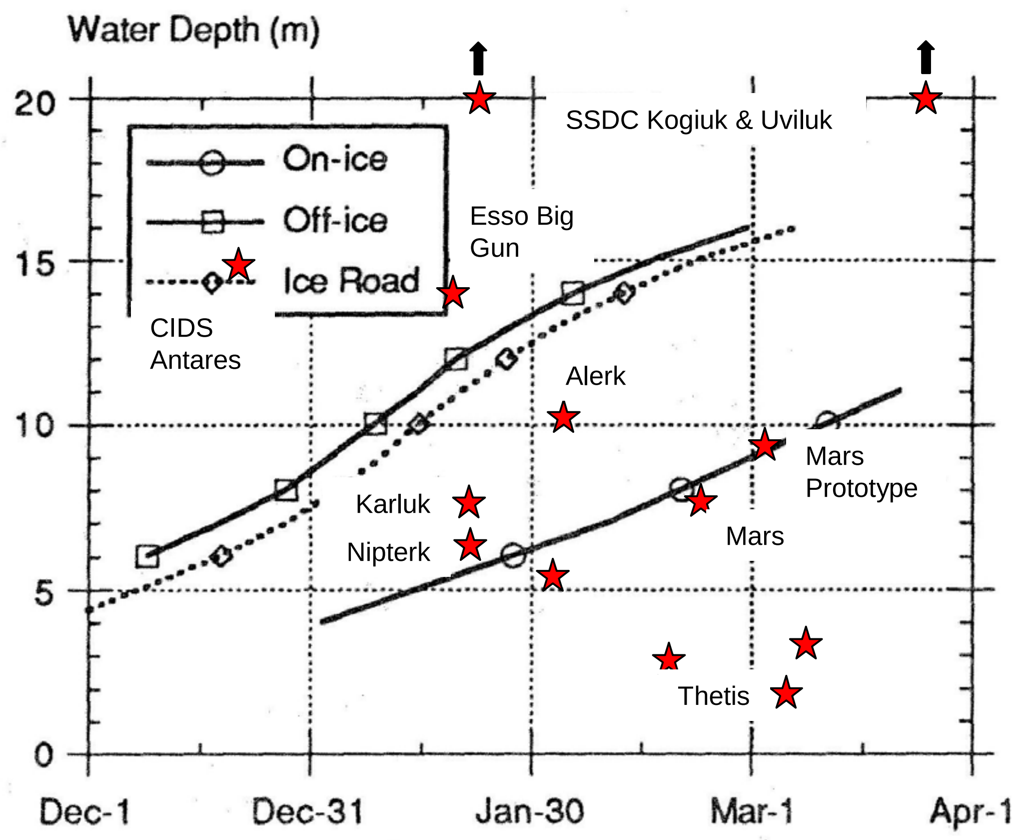


Figure 10.13: Comparison of On- and Off-Ice Spray Ice Construction Completion (Weaver et al, 1991, modified)

The logistics of delivering a drilling rig to the offshore island will have a large impact on the potential to extend the drilling season or increase water depth limitations. To date, land-based drilling rigs have been used, that have relied on grounded or floating ice roads to reach the ice island. The use of flooding or spraying techniques have been used to thicken ice roads to carry the required loads, with these operations being performed in parallel with island construction. The use of light equipment to create the road immediately following freeze up, followed by heavier units as the ice thickens is well established, and experience suggests that it should be possible to complete the road in a comparable time to island completion.

The demobilization of drilling rig and associated equipment must also be considered in relation to completion of drilling activities. The requirement for same-season relief well capability in the case of a blow-out would limit the date for completion of drilling activities. The construction of relief ice pads has been used to provide a platform for relief wells in the past, built after the main platform, with contingencies for surface preparation and access road construction to be undertaken during rig mobilization onshore. A study reported in COGLA (1990) indicated that an allowance of 25 days mobilization and 40 days drilling should be allowed for relief well operations in the case of a blow-out. An allowance of 9 days for dismantling and offloading the rig means that the end of risk-drilling of the main well should be complete 74 days ahead of the deemed last date for rig removal from the island. Alternatively, the use of heli-portable relief drilling rig could be considered to reduce this time (Neth et al 1983). The installation of well casing is considered to end the risk-drilling component, and subsequent logging and testing can be performed without allowing time for relief pad contingency. Relief well drilling is only required for the primary well into a particular play.

The closure of ice roads, although not necessarily limiting actual drilling operations, would limit the final allowable date based on the current practice of rig transportation. Data shows that offshore ice roads become unserviceable from early to late May, depending on location, showing a strong correlation with the onset of sustained above-freezing temperatures. The alternative of marine demobilization after break-up of the ice sheet has been investigated as part of the Nipterk ablation study (Poplin, 1990) and showed that this is feasible. In this case, the last date available for rig removal would be dictated by the start of island breakup – early July in the case of the Nipterk Island. The use of ablation protection and edge erosion protection measures could be used to delay this date, although there would be significant costs and risks associated with this method of demobilization.

The conclusion of the study into extended water depth operations for spray ice islands was that existing equipment, construction and mobilization/demobilization techniques allows ice platforms to be used in up to 9m water depth. Incremental improvements in equipment capacity with higher productivity would allow islands to be constructed into deeper water and it is considered that 12m water depth should not present a problem (Masterson 2005, personal communication). A typical schedule could take the form of that given in Figure 10.14 for on-ice construction in less than 10m water depth. The innovative use of off-ice techniques and marine demobilization of the drilling rig could extend the season sufficiently to allow operation to be performed in significantly deeper water, potentially providing increased construction and drilling time as shown by the schedule given in Figure 10.15. The earliest date for start of drilling operations depends on the method of rig mobilization – it may be onboard a vessel or structure frozen into the ice near the drill site, or it may require an ice road for transportation from a nearshore staging area. Large capacity pumps mounted on grounded structures and floating vessels have shown that ice islands can be constructed in water depths of up to 30m by making use of natural rubble. The study did not explicitly report the costs of extending water depth capability, and this should be the subject of further work to ensure that it still provides a cost effective solution.

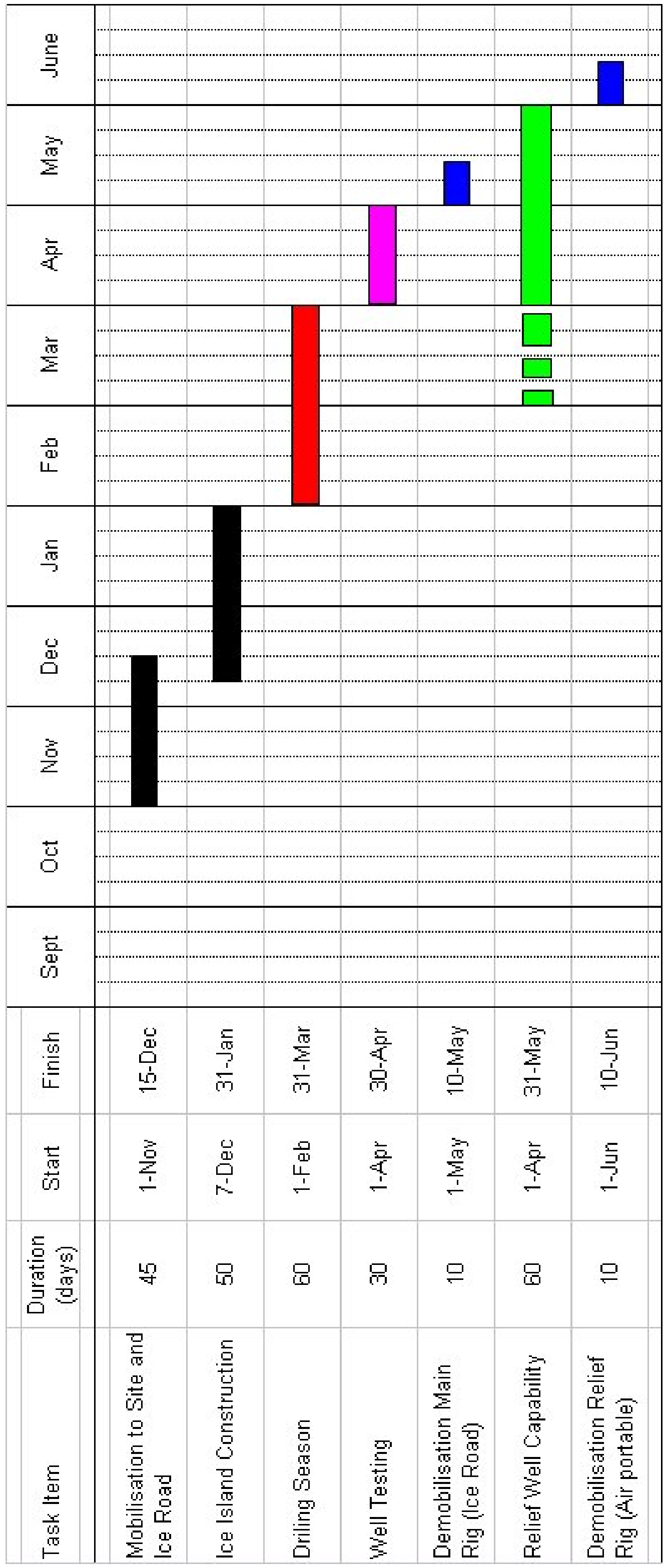


Figure 10.14: Suggested Schedule for On-ice Ice Island Construction Ice Road Demobilisation

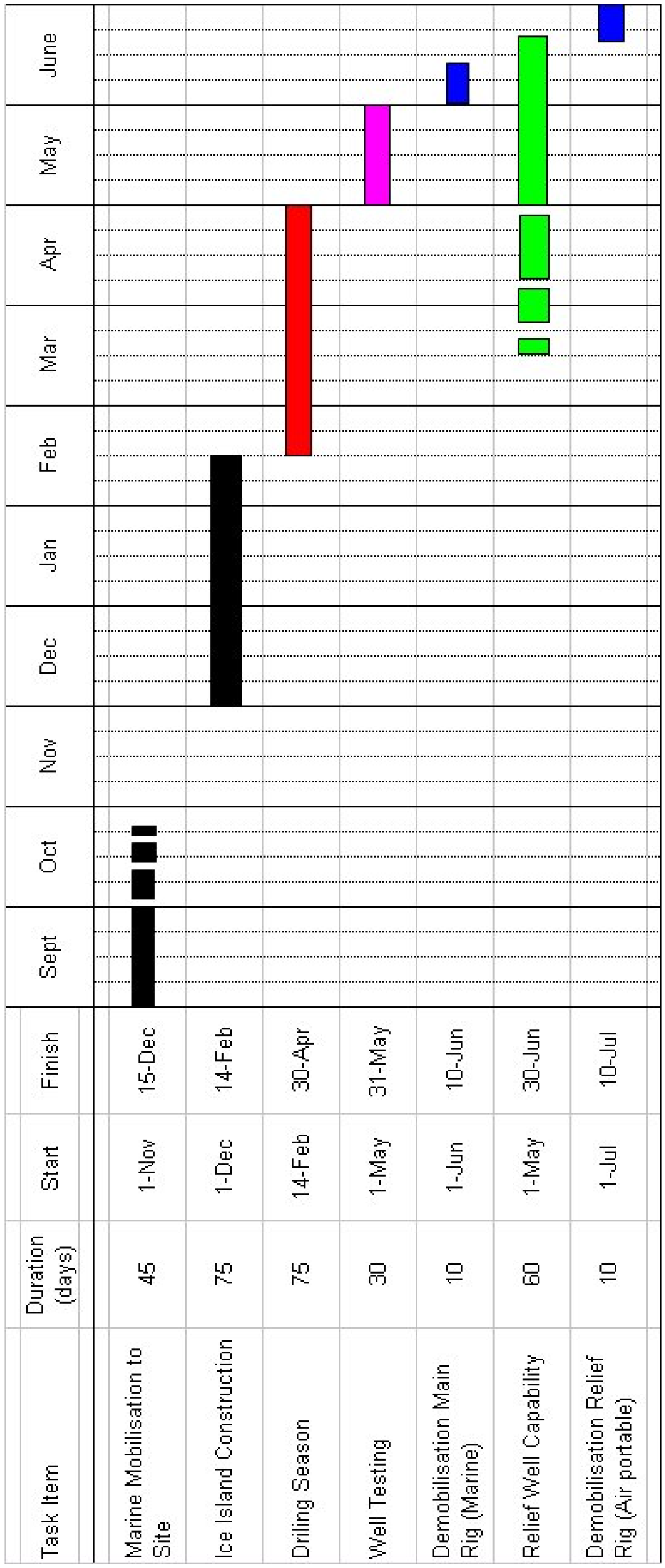


Figure 10.15: Suggested Schedule for Off-ice Ice Island Construction and Marine Demobilisation

10.4 Effects of Climate Change

Since the use of ice islands for exploration drilling relies on the ice material to operate at temperatures close to its melting point, the potential effect of changing climate patterns needs to be assessed. One such source is identified as the increasing global temperatures that have been measured over the past few decades, with much of this increase being attributed by many to the effect of human activities, particularly from burning fossil fuels. This section considers the potential effect of observed climate change on the use of ice islands for exploration drilling in the arctic.

In considering the particular climate parameters that affect the use of ice islands, the most important factors include:

- The onset of consistent below-zero temperatures, which determines the formation of first year ice;
- The onset of consistent -15 to -20^{o}C which allows efficient production of spray ice;
- The onset of consistent above-zero temperature which starts the melting process and determines the latest demobilization date due to break-up of ice roads.

Rigor et al (1999) performed a detailed analysis of surface air temperature for the entire Arctic region using in excess of 1600 land based meteorological stations, as well as numerous drift buoys and Russian North Pole drift stations between 1979 and 1997. The reanalysis was aimed at improving the level of correlation and accuracy of the data and establishing temperature trends in the Arctic, and included comparisons with other sources of published data. The conclusion was that, although annual temperatures are increasing on average, there are regional and seasonal differences that should be noted and have an effect on the use of ice islands. Points of particular interest for operations in the Beaufort Sea (termed Western Arctic by the authors) are summarized as follows:

- There is no significant warming or cooling trend in the Western Arctic, although other parts of the Arctic show a warming of approximately 1^{o}C per decade.
- Fall temperatures show a 1^{o}C per decade cooling in the Beaufort Sea and in Alaska, although the coasts of Greenland and Siberia show a warming of up to 2^{o}C per decade.
- During winter, a cooling trend of 2^{o}C per decade is seen over the Beaufort Sea and eastern Siberia, extending into Alaska. This contrasts with a 2^{o}C per decade warming trend in eastern Greenland, Europe and Eurasia.
- A significant warming of 2^{o}C per decade was noted over most of the Arctic during spring.

- No significant trend was determined for most of the Arctic summer.

- Analysis based on both temperature statistics and satellite imaging shows that the length of the melt season has increased by 2.6 days per decade in the Eastern Arctic, and shortened by 0.4 days per decade in the Western Arctic, with an average lengthening of 0.9 days per decade for the whole Arctic region. It is noted that these trends are considered insignificant, and that other authors have generated data that disagrees with these observations.

It is noted that these trends in surface air temperature agree with observations of sea ice concentration using satellite data, showing a shortening of the ice season in the eastern hemisphere and lengthening in the western hemisphere.

The paper also considers the effect of the Arctic Oscillation on the observed trends. The Arctic Oscillation refers to opposing atmospheric pressure patterns in northern middle and high latitudes, which composes a "negative phase" with relatively high pressure over the polar region and low pressure at midlatitudes (about 45 degrees North), and a "positive phase" in which the pattern is reversed. In the positive phase, higher pressure at midlatitudes drives ocean storms farther north, and changes the circulation pattern. In the positive phase, frigid winter air does not extend as far into the middle of North America as it would during the negative phase of the oscillation. Weather patterns in the negative phase are in general "opposite" to those of the positive phase, as illustrated below. Over most of the past century, the Arctic Oscillation alternated between its positive and negative phases. Starting in the 1970s, however, the oscillation has tended to stay in the positive phase, causing lower than normal arctic air pressure and higher than normal temperatures in much of the United States and northern Eurasia. It is concluded that the Arctic Oscillation accounts for 74% of warming over the eastern Arctic and 14% of cooling over the western Arctic. Figure 10.16 demonstrates the warming and cooling trends described above for each season.

Wadhams & Davis (2000) reports that surveys of the Polar ice pack indicate that it has thinned considerably between 1976 and 1996, with up to 40% reduction in thickness in places. There is, however, potential that a reduced thickness in some areas is offset by an increased thickness in others, and that the recorded thinning may not represent a net reduction in ice volume. The thickness of the Polar pack is not directly relevant to the issue of ice island operations in the nearshore areas, and reference to this work is just presented for information.

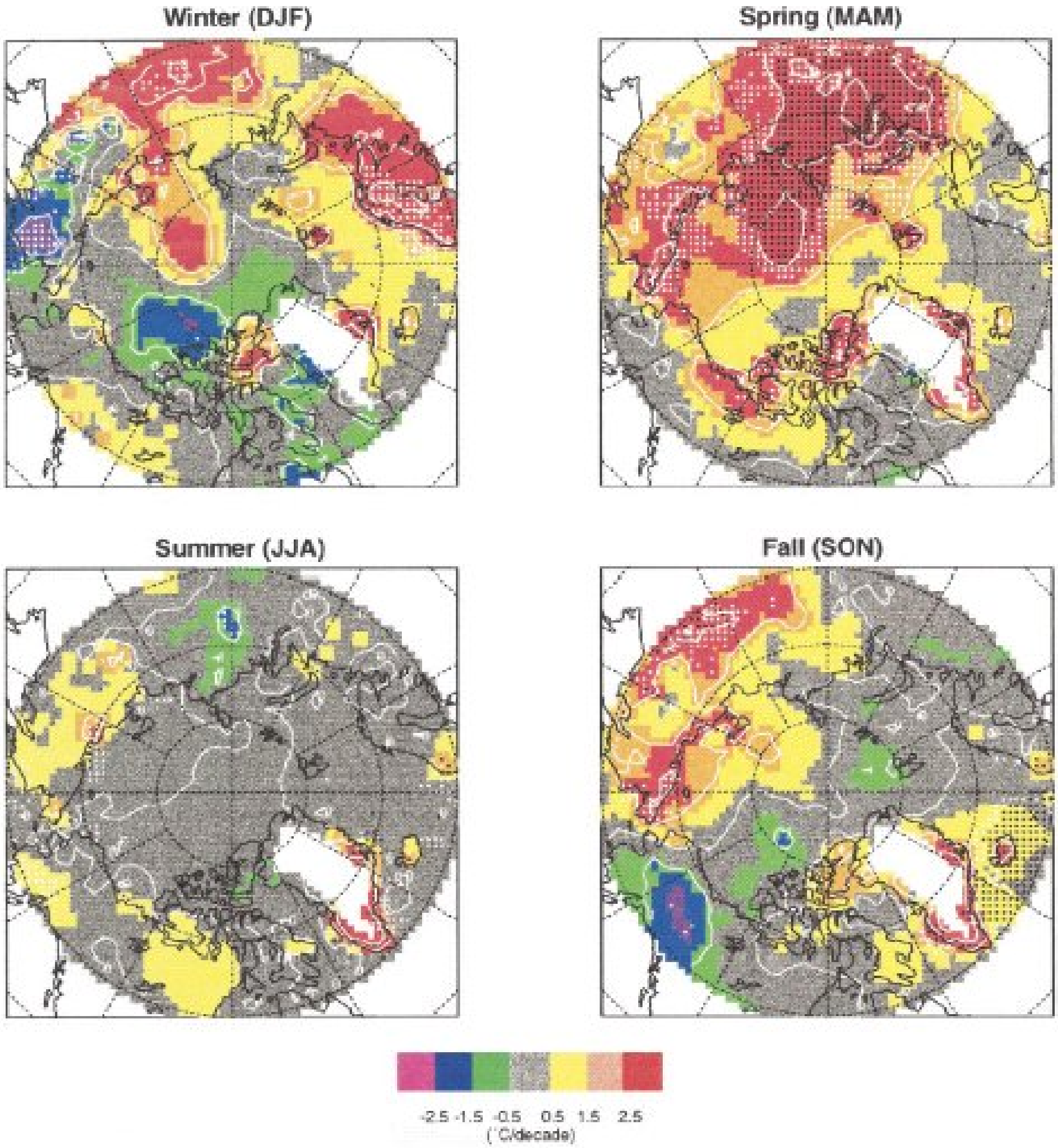


Figure 10.16: Seasonal Trends in Surface Air Temperature 1979-97 (Rigor et al 1999)

Recent measured environmental data has been downloaded from the MMS Beaufort Sea Meteorological Monitoring and Data Synthesis Project (MMS 2005) to allow comparison with climate normals for the Alaskan Beaufort Sea. Hourly temperature readings are available for the years 2001 to 2004 from monitoring stations located at Northstar, Endicott, Badami, Milne Point and Cottle Island on the Alaska North Slope. This data has been used to provide a comparison between published longterm trends in climate normals and actual recorded data from recent years. The data from each of the 5 monitoring sites was overlain and mean values used in the analysis. Figures 10.17 to 10.20 present the data used for this analysis. The figures are labeled (shading) to indicate times at which the air temperature is below -20^{o}C (suitable for spray ice production) and above 0^{o}C (the melt season).

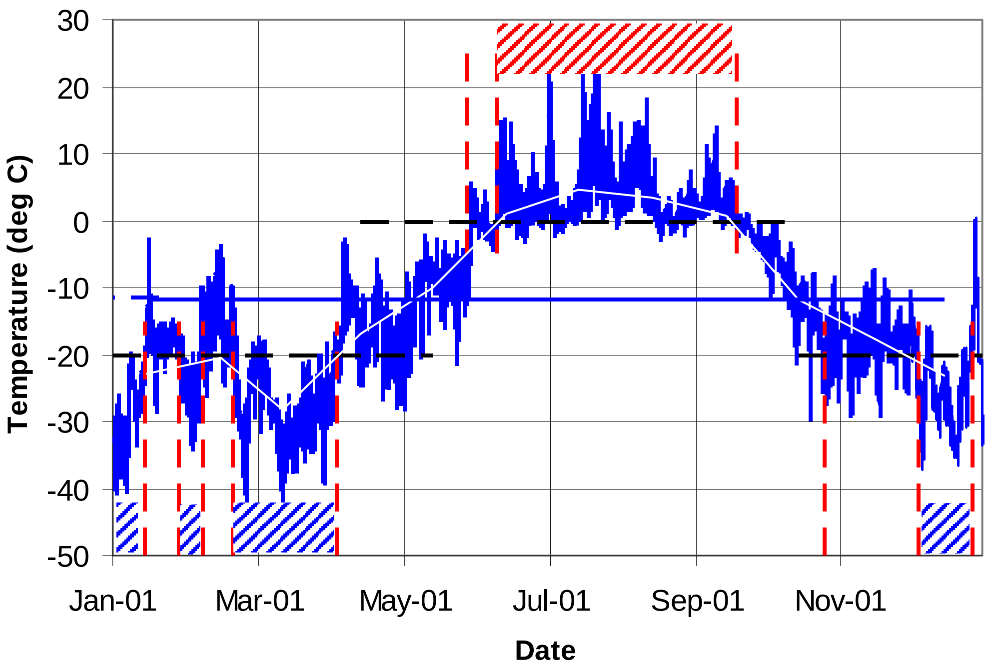


Figure 10.17: Temperature Data for 2001, Alaska North Slope

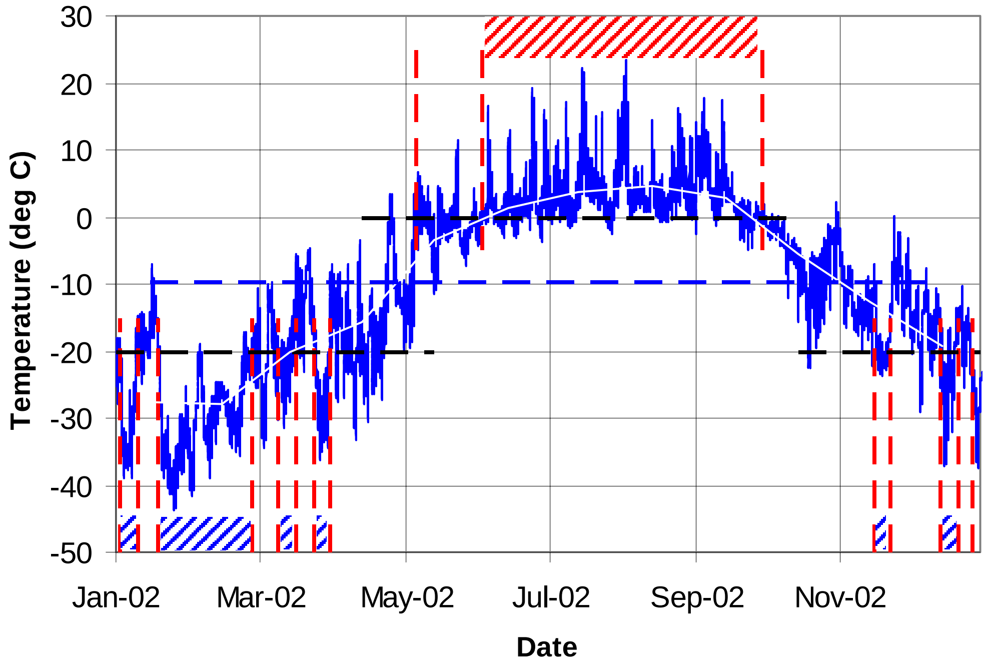


Figure 10.18: Temperature Data for 2002, Alaska North Slope

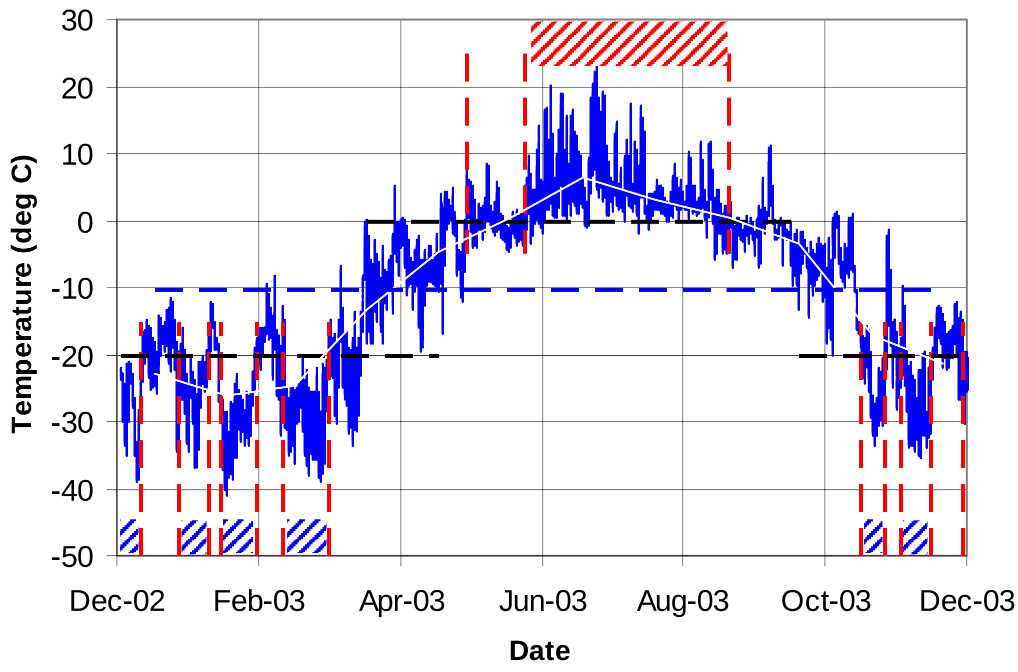


Figure 10.19: Temperature Data for 2003, Alaska North Slope

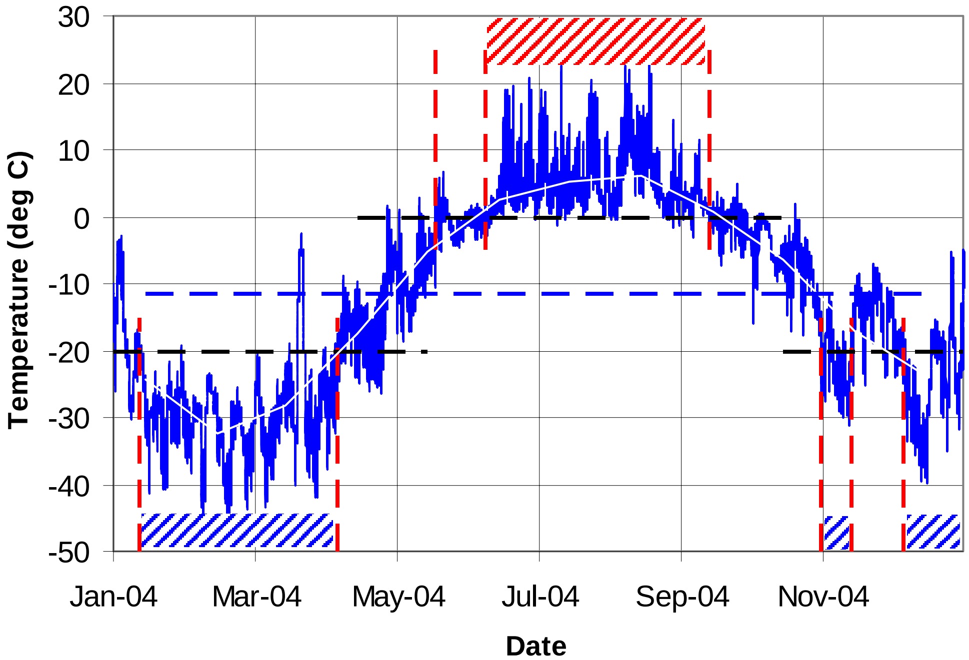


Figure 10.20: Temperature Data for 2004, Alaska North Slope

Tables 10.1 and 10.2 summarise the pertinent data extracted from the temperature records. The tables focus on the parameters that determine the length of the season with respect to the use of ice islands. Table 10.1 considers the onset of temperatures less than -20^{o}C for each year, with the date of initial onset, and date when temperatures are consistently lower than -20^{o}C noted. The number of days during which the temperature was less than -20^{o}C was also noted, with a distinction made between the whole winter season, and a cut-off date of Feb 1st as required for most practical situations. The longterm climate data was used as a comparison using average monthly values. Comparison of longterm data with individual measurements can be misleading in that the monthly average temperature may be less than -20^{o}C suggesting 30 days of good operating conditions, but not every day actually provides such temperatures. Nonetheless, the data comparison is useful. Table 10.2 Considers the length of the summer (melt) season by comparing the onset of above-zero temperatures, both initial exceeding and consistently above 0^{o}C. This data is useful for determining the onset of deterioration of ice conditions and determines restrictions to demobilization using ice roads. As in Table 10.1, the data is compared to average monthly values from longterm data. Figure 10.21 also presents this data graphically.

The data from 2001 to 2004 shows that in general, the temperature drops to less than -20^{o}C in the first 2 weeks of November, and starts to stay consistently below that value between mid-November to mid-December. Temperatures rise consistently above -20^{o}C in the first week of March. The data shows that the duration of temperatures below -20^{o}C varies considerably, as does the number of days with these low temperatures. In general, the number of days at less than -20^{o}C is only 60% to 70% of the overall duration of cold weather, based on the 3 winters analysed. It should be noted, however, that other factors also have an effect on the conditions required for good spray ice productivity, such as ice conditions and wind speed and direction.

The length of the melt season (temperature above 0^{o}C) is consistent with the longterm conditions, and that there is limited variation between the years analysed. The initial increase of temperature above 0^{o}C occurs between the second and last week of May, with consistent above-zero temperatures experienced from the second or third week of June. Freezing temperatures start again from mid-September. The melt season is approximately consistent at 100 days and close to longterm trends. In particular, 2002 seems to have had a longer summer and shorter winter season. In contrast, 2003 seems to have had a shorter than usual summer and earlier start of the winter season.

Table 10.1: Winter Season Data 2001 to 2004, Alaska North Slope

Winter Season	**Start Date <-20^{o}C**	**Start Date Consistently <-20^{o}C**	**Stop Date >-20^{o}C**	**Winter (<-20^{o}c) Total Duration (days)**	**Total Days <-20^{o}C (days)**	**Days <-20^{o}C Before Feb 1 (days)**
2000/2001	-	-	5-Apr			
2001/2002	26-Oct	4-Dec	1-Apr	118	84	42
2002/2003	16-Nov	16-Dec	30-Mar	104	78	29
2003/2004	10-Nov	10-Nov	4-Apr	146	106	42
2004/2005	31-Oct	5-Dec	-	-		
Longterm	-	15-Nov	9-Apr	145	-	77

Table 10.2: Summer Season Data 2001 to 2004, Alaska North Slope

Summer Season	Annual Average Temp (°C)	Start Date >0°C	Start Date Consistently >0°C	Stop Date <0°C	Summer (>0°C) Total Duration (days)	Summer (>0°C) Consistent Dur'n (days)
2001	-11.7	29-May	11-Jun	19-Sep	113	100
2002	-9.7	7-May	21-Jun	30-Sep	146	101
2003	-10.2	27-May	21-Jun	15-Sep	111	86
2004	-11.6	18-May	9-Jun	13-Sep	118	96
Longterm	-11.8	-	4-Jun	17-Sep	-	105

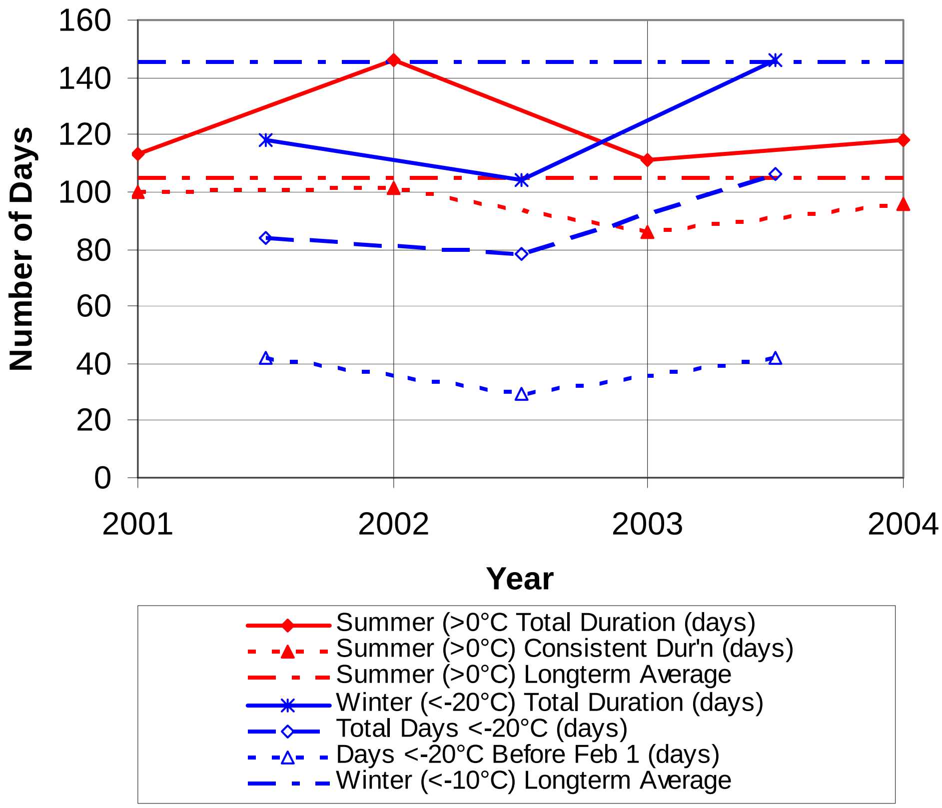


Figure 10.21: Seasonal Temperature Data 2001 to 2004, Alaska North Slope

The temperature data for the 2001 to 2004 seasons has also been plotted to allow direct comparison with longterm climate data. This is presented in Figure 10.22 in terms of hourly readings, and in Figure 10.23 using derived monthly mean values. The plots show that in general over the past 4 years, the summer temperatures have been cooler than historic values, while winter temperatures have been slightly warmer, particularly at the beginning of the winter season.

The data presented in this section suggests that any effects of climate change will have negligible effect on the use of ice islands in the near future, and that any perceived longterm trends are masked by the scatter of data obtained from year to year. The data presented by Rigor et al (1999) suggests that fall and winter surface air temperatures show a decreasing trend in the Western Arctic, in contrast to measured data in other parts of the Arctic region.

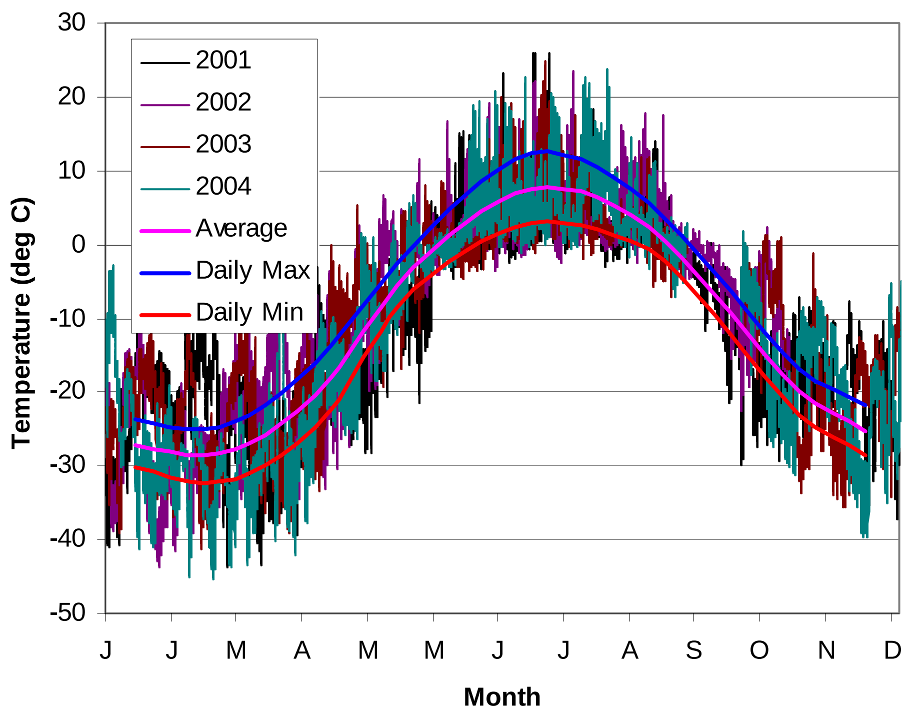


Figure 10.22: Comparison of Recent Hourly Temperature Data with Historic Climate

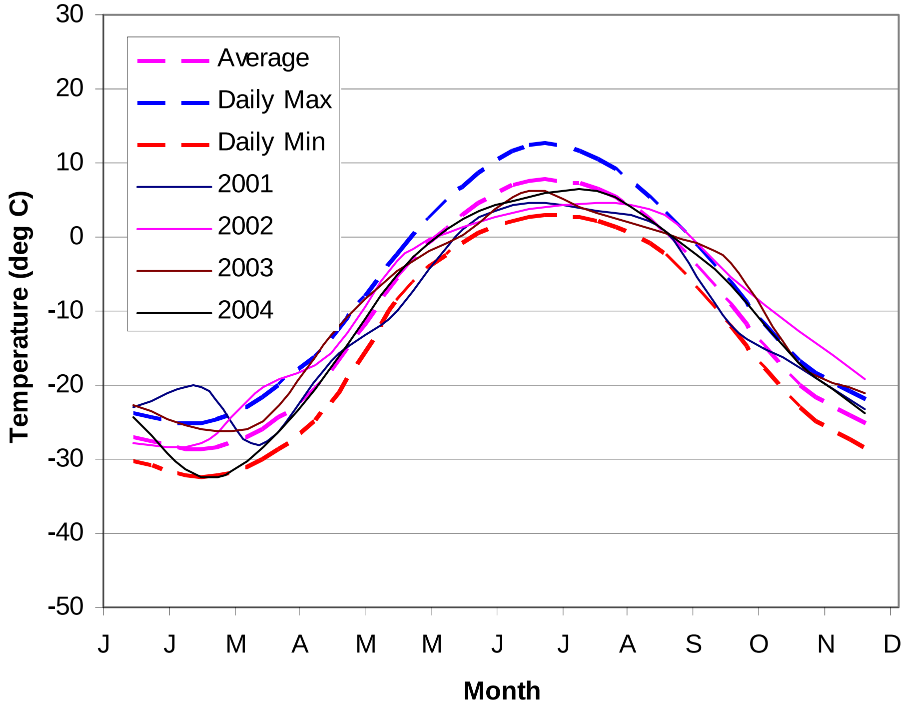


Figure 10.23: Comparison of Recent Monthly Temperature Data with Historic Climate

11.0 INNOVATIVE ADVANCES

The use of spray ice construction techniques has demonstrated the feasibility and cost effectiveness of this method for forming ice islands for offshore exploratory drilling. A number of variations have been used or proposed, which are aimed at further reducing the cost or risk of operations. A number of these techniques have been reviewed and may be worthy of further development.

- Use of pre-formed ice to improve productivity during warm weather, when spray ice production becomes inefficient. Szilder et al (1991) developed a mathematical model to compare the efficiency of water flooding, spraying and flooding with an ice/water mixture. The analysis showed that flooding and spraying can be inefficient, particularly at warmer temperatures as a result of surface area limitations (flooding) and supercooling effects (spraying). The use of ice chips saturated with water was largely independent of air temperature and allowed high build-up rates to be maintained. Figure 11.1 presents the results of this analysis in terms of build-up rate for various methods. This system was used in practice at the Thetis ice island (Sandwell 2003b), in which asphalt strippers were used to produce chipped ice from near shore areas. These chips were transported to the ice island by dump truck, leveled and the voids filled with water. It was noted that this was effective in allowing island construction to proceed during warmer weather events.

- Ice loads acting onto the island can be controlled by reducing the thickness of the natural ice sheet in the vicinity. Ice movements in the near shore landfast zone are subjected to relatively small movements (tens of metres) through the season, and so the area of reduced thickness should be sufficiently extensive to absorb this movement. Tests have been performed in the field aimed at reducing the ice thickness, including the use of slot cutting and placement of snow berms on the ice surface (Poplin & Weaver, 1992). Snow harvesting was considered inefficient due to the thin coverage and limitation on equipment weight, but a number of berm configurations up to 2m high were adopted and compared. The use of snow fences to encourage snow build-up was considered more effective and less labour intensive. The resulting snow berms resulted in reducing ice thickness by over 40% over a season, although issues such as the risk of flooding of the depressed ice sheet needs additional study. Figure 11.2 presents the snow berm configurations used to reduce ice thickness. Thinning of the ice sheet using planning mechanical equipment was considered at the Thetis ice islands (Sandwell, 2003b) by planing a width of 6m around the island circumference. The ice thickness could be reduced in this way from 1.75m to 1.1m, allowing the design load to be reduced correspondingly. This technique relies on a good understanding of the ice movement characteristics, and may not be applicable for long duration drilling or in areas of frequent, large ice movements through the season. Further, these techniques must be proven to be reliable prior to their use on an operational basis, as the consequences of unexpected behavior are significant.

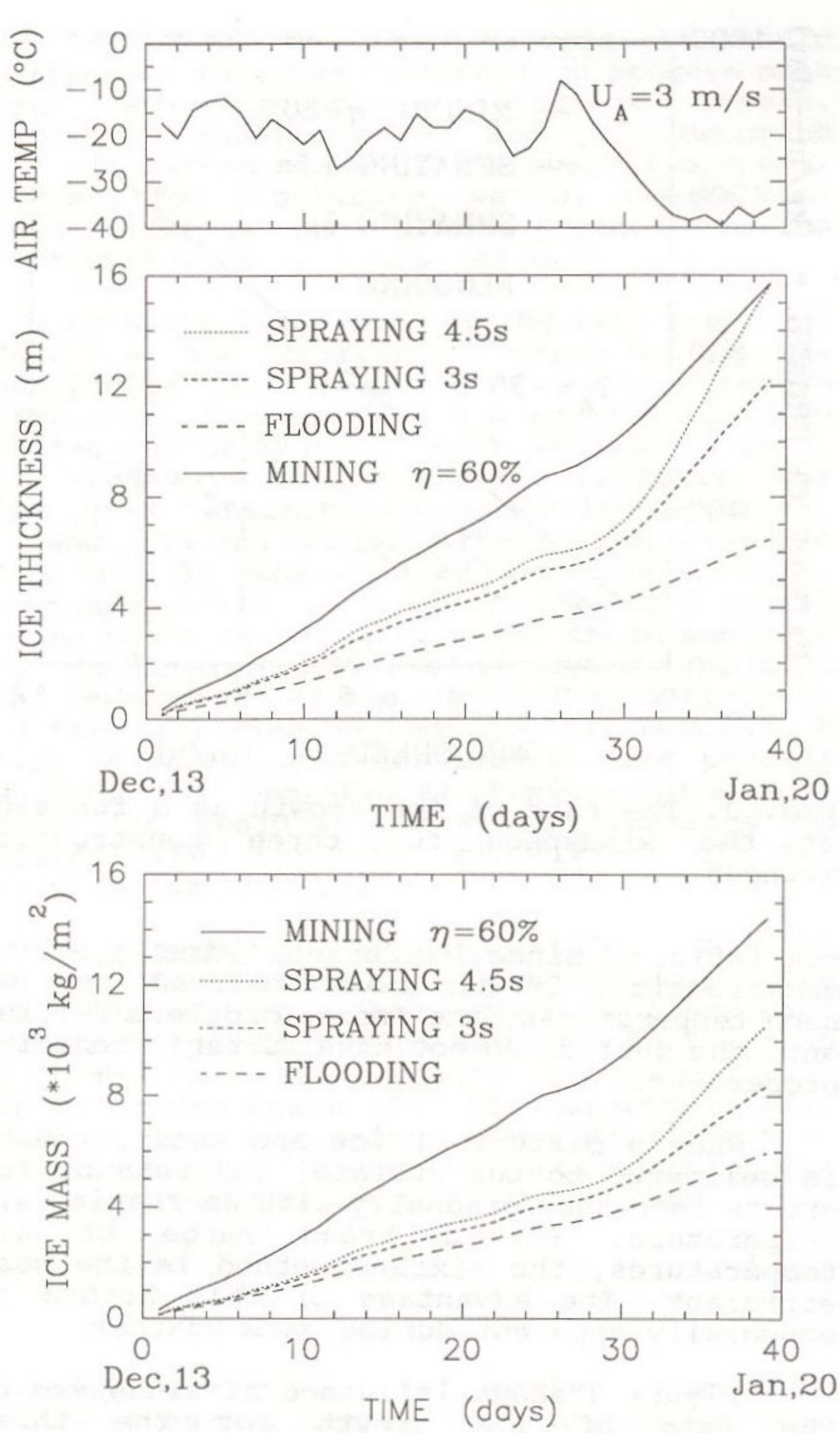


Figure 11.1: Comparison of Build-up rates for Various Ice Production Methods (Szilder et al 1991)

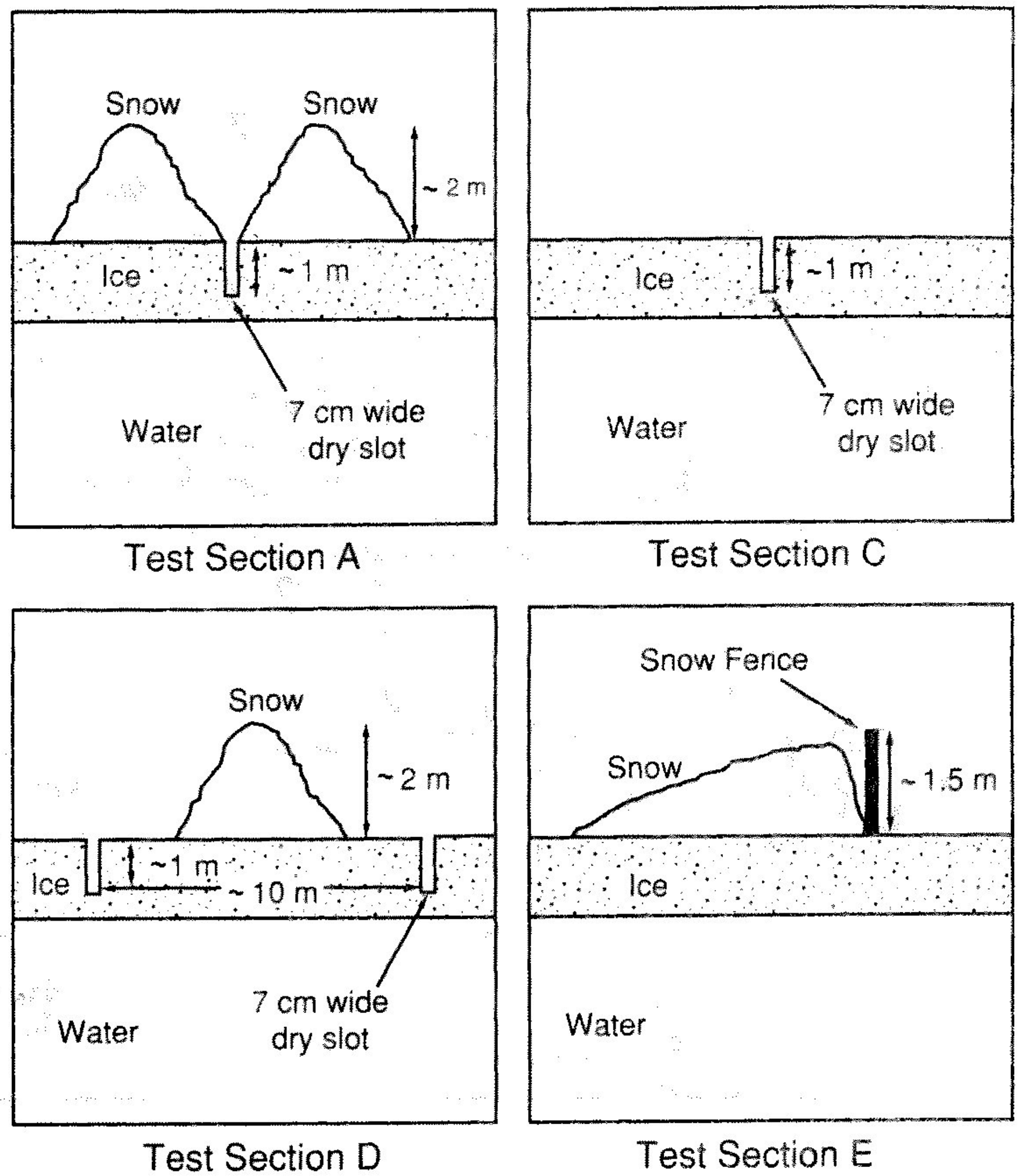


Figure 11.2: Snow Berm and Slot Configuration for Reduction of Ice Thickness (Poplin & Weaver 1992)

- Methods to reduce the volume of spray ice required to form a drilling platform have been investigated by a number of practitioners. Many of the efforts have focused on methods of inducing rubble build-up in early winter as ice cover forms and the ice is still mobile. Potter et al (1982) tested an ice boom system made up of steel "dolphin" structures ballasted to the seabed and linked with wire booms. These were partially successful in creating rubble piles, as shown in Figures 11.3 and 11.4. Similar structures were proposed by O'Rourke (1984).

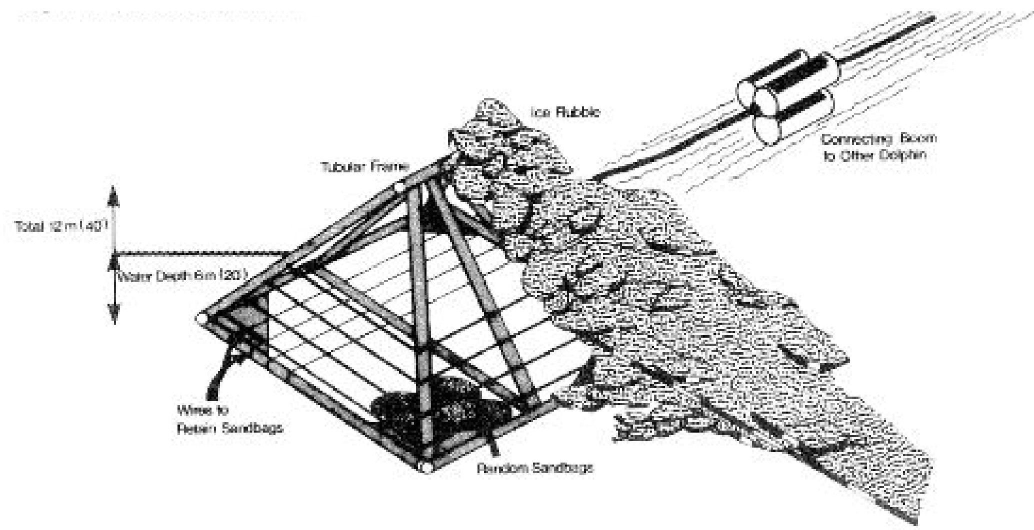
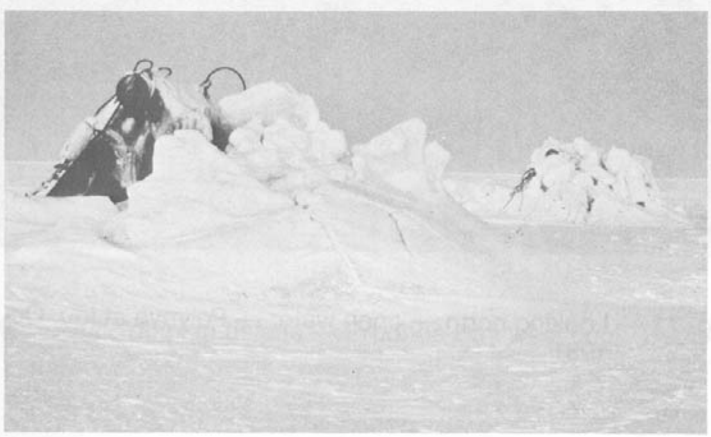


Figure 11.3: Proposed Dolphin Structures for Generating Rubble Build-up (Potter 1982)

Arctic dolphins — Oct. 27, 1981

Arctic dolphins — Nov. 16, 1981



Arctic dolphins — Dec. 8, 1981

Figure 11.4: Rubble Build-up on Arctic Dolphin Structures (Potter, 1982)

- Observation construction techniques are becoming widely used in the construction industry, particularly for geotechnical engineering applications. These methods have shown that robust designs can be implemented, but that efficiencies can be realized during construction based on ongoing monitoring. Examples of possible applications include accounting for measured natural ice thickness which may be less than used in the design, or the production of denser spray ice than required in the design. The extrapolation of ice thickness build-up charts such as in Figure 8.1 would allow the island design to account for actual ice conditions rather than historical values. Both of these parameters can allow a reduced ice volume to be used in the final constructed island, and were used for construction of the Thetis ice islands (Sandwell 2003b). A good interface is required between the design and construction teams, and rigorous management of the process is required for successful implementation of this system.

- Alternative construction practices have been considered for the construction of offshore ice structures, which could find applications for exploration drilling. O'Rourke (1984) considered a number of such new ideas, such as towing, scooping natural ice to the drilling location in order to reduce the required artificial ice volume production. The use of nets to trap ice was also considered a feasible option for holding deposited ice in place. Figures 11.5 and 11.6 present some of these methods, which could be combined with spray ice construction techniques to develop cost effective structures.

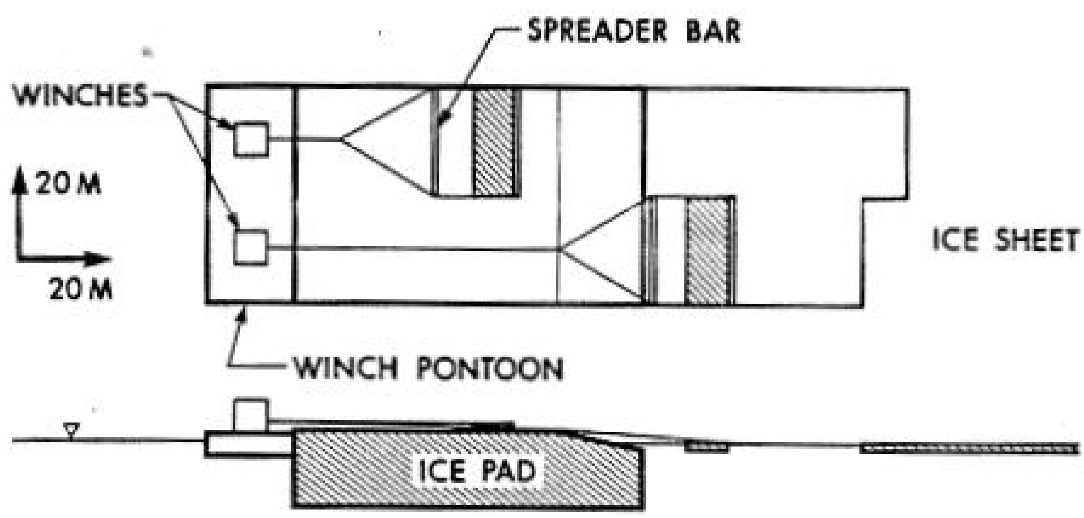


Figure 11.5: Pull-up Barge System for Rafting of Natural Ice (O'Rourke 1984)

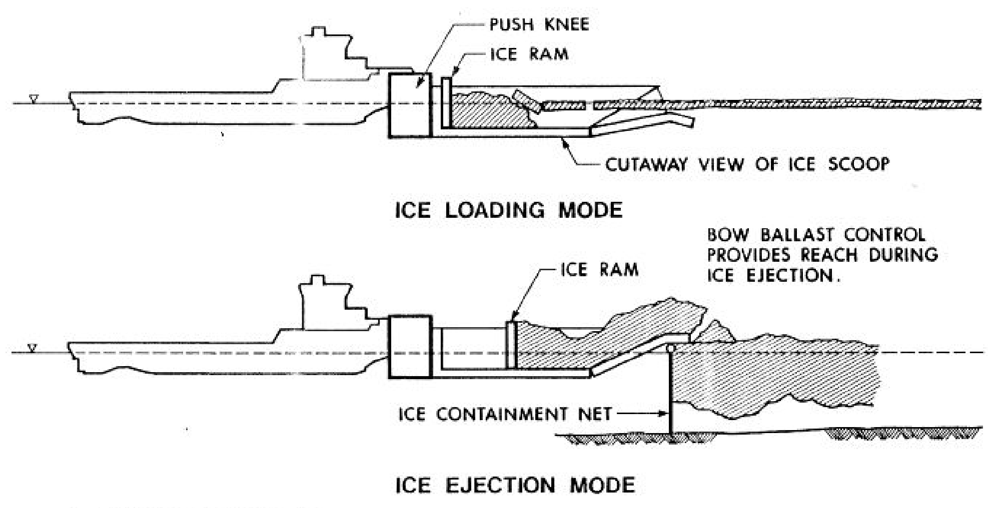


Figure 11.6: Ice Scoop Barge system for Harvesting of Natural Ice Sheet (O'Rourke 1984)

12.0 DEMONSTRATION CENTRIFUGE TEST

12.1 Background

Centrifuge modeling is a useful tool when modeling gravity-dependent phenomena in geotechnical systems as described by Schofield (1980) & Murff (1996). Centrifugal acceleration is used to simulate increased gravity and allows for correspondence of stress fields between model and full-scale, permitting accurate modeling of geotechnical and other gravity-dependent phenomena. Such modeling has regularly increased general understanding, and permitted calibration and verification of numerical and theoretical models of full-scale situations.

The geotechnical centrifuge modeling technique accounts for the stress-dependent behaviour of soils. Soil models placed at the end of a centrifuge arm are rotated to achieve an inertial radial acceleration field, which replicates Earth's gravity but at a higher level. If the same soil is used in both the model and prototype and the soils both have similar stress histories, then soil stress similarity is correctly modeled. When the soil model is subjected to an accelerated inertial stress field of N times Earth's gravity, the vertical stress at depth h_m in the model will be equal to the prototype vertical stress at soil depth h_p (where $Nh_m = h_p$). This is the basis of centrifuge modeling and the associated scaling laws, that stress in the model and prototype are equal at a homologous point by accelerating a model of scale 1:N to N times Earth's gravity (g). The principles of geotechnical centrifuge modeling are suitable for considering the ice/seabed interaction for a grounded ice island, since the sliding mechanics are a function of stress state of the ice and soil. Table 12.1 presents typical centrifuge scaling for a range of test parameters. The C-CORE centrifuge facility is shown in Figure 12.1.

A demonstration centrifuge test has been performed to compare the sliding characteristics of a grounded rigid plate structure with that of a grounded spray ice structure. A review of design considerations used in practice shows that grounded ice islands are assumed to act as rigid structures, and that the ultimate failure condition is characterized as sliding of a rough plate along the seafloor. Processes such as penetration of the broken natural ice sheet into the seabed, displacement of soft clay seafloor material during grounding and non-uniform stress conditions under lateral loading all add considerable uncertainty to the design process, and simplified procedures have been developed to provide safe, conservative structures. Consideration of alternative design factors may allow economies to be made by removing conservatisms in the design process.

The demonstration test was performed by loading two imitation ice islands grounded onto a soft clay seabed. One island was placed on top of a rough rigid plastic plate, while the other was placed directly onto the clay seabed. Spray ice was made in a walk-in coldroom set to –20^{o}C using a water / compressed air mixture. The spray ice was placed within a floating ring to allow it to keep its shape, which also provided a connection to the loading mechanism. The model was constructed in the laboratory at 1g, prior to being placed in the centrifuge and accelerated to 100g (100 times earth's gravity) in a climate controlled package. Each island was then loaded in turn to failure, and the load and displacement behaviour was measured.

Table 12.1: Typical Centrifuge Scaling Factors

Parameter	Scale Factor
Gravitational Acceleration	N
Macroscopic Length	1/N
Mass	$1/N^3$
Stress	1
Fluid Flow Velocity	N
Heat Flux	N
Time (Diffusion)	$1/N^2$
Time (Conduction)	$1/N^2$
Temperature	1

Figure 12.1: C-CORE Geotechnical Centrifuge

12.2 Objectives

The objectives of the centrifuge test were as follows:

- To demonstrate that the production of spray ice can be undertaken in laboratory conditions to allow testing of the material properties and behaviour under particular conditions;
- To demonstrate that centrifuge testing is an appropriate technique that can be applied to the study of ice island design issues, and;
- To investigate the behaviour of a spray ice island under lateral load, and compare differences between design assumptions and observed failure mechanisms.

12.3 Spray Ice Production

The C-CORE walk-in cold room facility, measuring approximately 3.1m by 4m in area and 2.6m in height was used to prepare and collect spray ice with which to build the model ice islands for the centrifuge tests. The spray ice was produced by spraying water through a specially made nozzle incorporating a water and compressed air inlet. The quantity of spray ice produced depends on the ability of the cold room to maintain the required cold temperature, as the freezing process adds significant heat to the cold room. A quantity of bulk sand was therefore used as a heatsink to add thermal inertia to the system prior to the start of spraying. Three nozzle configurations, with different inlet and outlet diameters, were systematically tested, leading to the selection of the one which produced the most consistent spray ice with the right properties. The selected nozzle is shown in Figure 12.2. The compressed air was supplied to the nozzle at a constant pressure of 400kPa (60psi) and chilled water was drawn up by suction through an insulated line running perpendicular to the airflow. A line attached at an angle to the flow was left open to the atmosphere to aid in the dispersion and cooling of the stream.

The initial cold room temperature was set to -20ºC. The spray process was undertaken in stages of approximately 15 minutes, during which time the cold room temperature increased gradually to -15ºC. The spraying was then stopped and the cold room left to cool back to the original starting temperature. This process was repeated several times to produce the required volume of ice. A grain size analysis was performed on the resulting spray ice product, with the results given in Figure 12.3. The measured grain size compares well with reported values from production under laboratory and field conditions (Steel 1989).

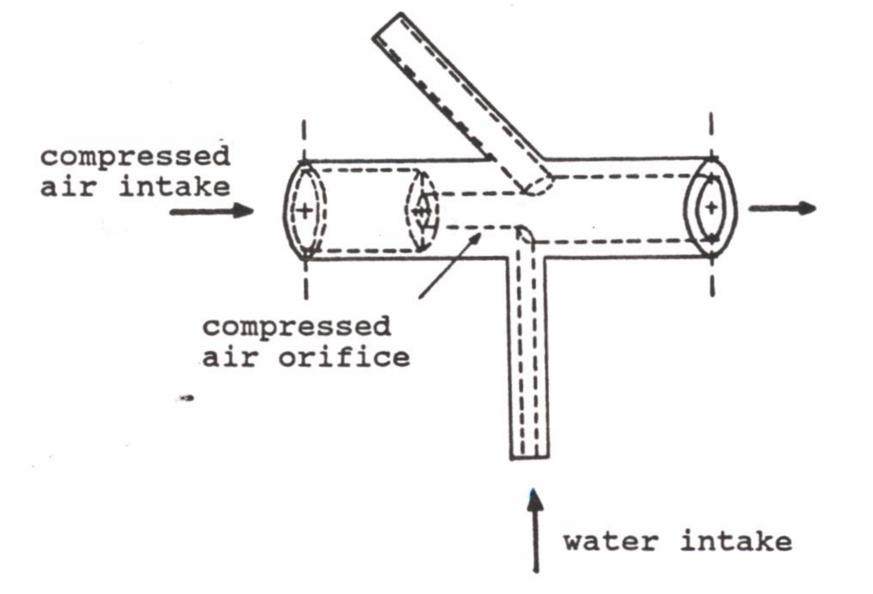


Figure 12.2: Nozzle Used for Spray Ice Production in the Laboratory

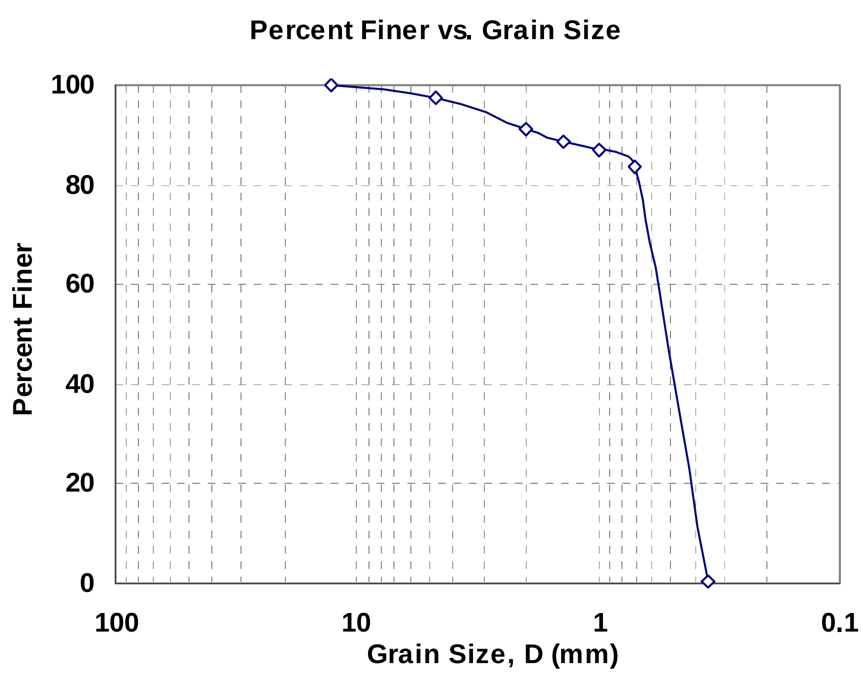


Figure 12.3: Results of Grain Size Analysis of Spray Ice Produced in the Laboratory

12.4 Model Package

The soil bed used in the centrifuge test was made up of a mixture of 75% Sil-Co-Sil silt and 25% Speswhite Fine China Kaolin clay. These materials are used extensively in centrifuge modeling due to their consistent properties and ability to reproduce required soil parameters. The silt and kaolin were mixed in a drum-type mixer, followed by consolidation to reach the required moisture content and strength for testing. The final moisture content of the soilbed was 22% and corresponding dry density was 1690kg/m^3. A series of Hand-Vane shear tests was conducted, indicating an undrained shear strength of the consolidated soil of approximately 10kPa.

On completion of consolidation, the sample was extruded from the consolidation box, cut to the required size, and placed into an insulated test package. The entire test container was then placed within the cold room set to -1ºC. The model was saturated by slowing adding saline water with a concentration of 3ppt and a temperature of -1.5ºC. In this way, the freshwater spray ice and saline surface water would remain in equilibrium at a temperature of -1^{o}C.

Several areas of temperature control were required throughout the centrifuge test: the temperature in the islands, ambient air temperature above the islands and the water/seabed temperature. An insulated aluminum rectangular strongbox was used to contain the model, with the base and inner walls of the main structure enclosed with extruded polystyrene insulation. To enable cooling of the ambient air at the model surface, the C-CORE centrifuge is equipped with a refrigeration unit, with cooling of the air accomplished by re-circulating glycol refrigerant through a rotary joint between the test package and refrigeration unit. A heat exchanger is mounted within the test package, which provides uniform cooling from the lid of the package. The volume flow rate of liquid refrigerant passing through the heat exchanger controls the air temperature within the insulated test package. The entire model test container and lid were pre-chilled in the cold-room, enabling the test model and ancillary equipment to act as a thermal sink. This ensures that the soil body and pore water reach a uniform and stable temperature prior to being loaded on the centrifuge arm.

12.5 Centrifuge Model Design

The assumed prototype of the spray-ice islands had freeboard of 6m in a water depth of 6m. Limitations in the physical size of the centrifuge package prevented a realistic ice island diameter (200 to 300m) to be modeled, resulting in a smaller aspect (width to height) ratio being used. Table 12.2 presents the prototype and model scale islands used for the test. The model was constructed in the laboratory at 1g, prior to being placed in the centrifuge and accelerated to 100g in the climate- controlled package.

Table 12.2: Prototype and Model Dimensions

Parameter	Prototype Scale	Model Scale
Island Diameter	30 m	300 mm
Water Depth	6 m	60 mm
Island Freeboard	6 m	60 mm

The spray ice produced within the cold room was placed into two plastic rings, which were used to shape the ice-islands. The rings were 300mm in diameter, 40mm in height and floated on the water surface. The water depth was 60mm as shown in Table 12.2. Each ring was held in position as the spray ice was scooped into the water within the ring until the final height of the island was achieved. A small diameter steel cable was connected from the back face of the plastic ring, passing through the island to allow a load to be applied to simulate ice loading. The initially dry spray ice became saturated as it was added to the model and as the model grounded on the soilbed, this process was continued until the required freeboard was reached. It was noted that the ice continued to be saturated, even in the above water section due to the small vertical height of the model. Island A was grounded directly on the soilbed, whereas Island B had a rough rigid plate placed between the ice and the soilbed. Figure 12.4 shows the plastic ring structure and the completed ice islands.

Figure 12.4: Ring for Formation of Ice Islands, and Completed Ice Island Models

A pneumatic cylinder was used to pull each island horizontally during the centrifuge test to simulate failure due to ice loading. The cylinder was connected to a control transducer which allowed the applied load to be controlled. Each cylinder was connected to one ice island model via the loading cable wire passed through a pulley. The maximum supply air pressure of 700kPa (100 psi) produced a maximum of 11.7kN pulling load. Figure 12.5 presents a schematic of the model layout and loading mechanism.

12.6 Instrumentation

The model test incorporated a number of instruments to allow the test to be controlled and its behaviour to be interpreted. The instrumentation consisted of the following units:

- The pulling load applied to islands was measured by a load cell, which was part of the loading cable system.

- The horizontal displacements of the islands were recorded using string potentiometers mounted on each ram of the loading cylinder. Since the ram and island were connected by a cable through the pulley, the vertical displacements of the ram represented the horizontal sliding displacement of the islands.

- The vertical settlement of the island surfaces were recorded using linearly variable differential transformers (LVDTs). The LVDTs were mounted on aluminum angle beams that spanned the width of the model container, with two LVDTs placed on top of each island.

- The temperatures within the test package were monitored using thermistors placed at key locations throughout the model. Two thermistors were placed in the soil bed directly below each ice island. A further two thermistors were placed inside the body of each ice island. The temperatures in the ambient air, water and soil bed were also monitored using thermistors. All thermistors were calibrated using an ice bath to enhance the accuracy provided by the manufacturer's calibration values.

- Four pore pressure transducers (PPTs) were placed within the model to monitor the pore water pressure throughout the test. One PPT was installed directly below each ice island, and another 2 PPTs were installed in the water and in the soil bed outside of the influence of the islands to determine water level in the model.

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All instrumentation was monitored and sampled using DAC Express software and subsequently processed and plotted using Matlab software. Data was sampled at 2 second intervals to allow real-time observation during the test.

Table 12.3 details the instrumentation showing designated labels for reference in the discussion and plots of results.

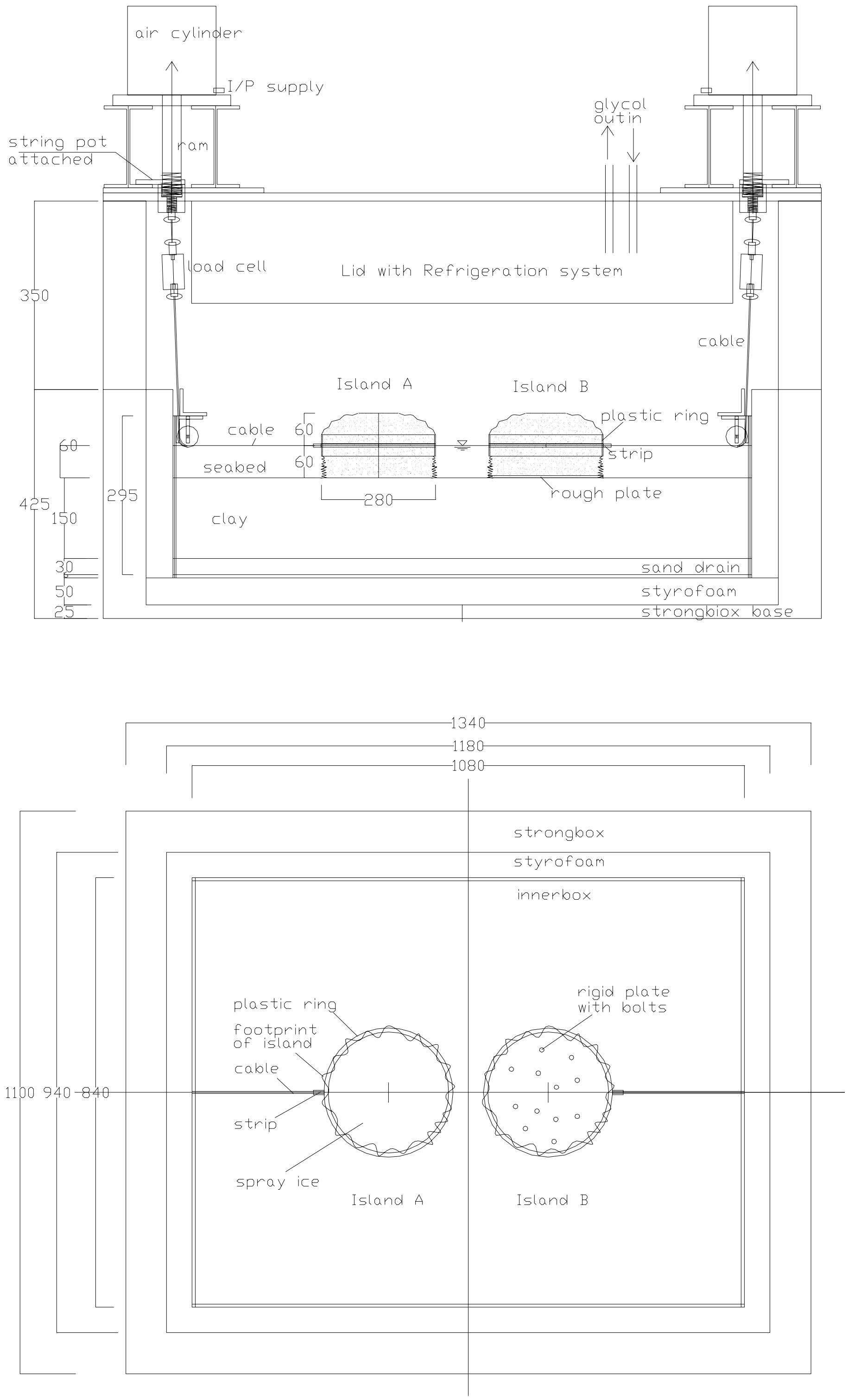

Figure 12.5: Model Layout and Loading Mechanism

Table 12.3: Designation of Test Instrumentation

Instrument Designation	Instrument Type	Instrument location	Engineering Units
LC1	Load cell	Iisland A	kN
LC2	Load cell	Iisland B	kN
SP1	String pot	Iisland A	mm
SP2	String pot	Iisland B	mm
PPT1	PPT	Soilbed, 20mm directly below island A	kPa
PPT2	PPT	Soilbed, 20mm directly below island B	kPa
PPT3	PPT	General soilbed away from islands	kPa
PPT4	PPT	Under water above seabed	kPa
T1	Thermistor	Soilbed, 20mm directly below island A	^oC
T2	Thermistor	Soilbed, 20mm directly below island B	^oC
T3	Thermistor	General seabed temperature	^oC
T4	Thermistor	General water temperature	^oC
T5	Thermistor	Island A, high elevation	^oC
T6	Thermistor	Island A, low elevation	^oC
T7	Thermistor	Island B, high elevation	^oC
T8	Thermistor	Island B, low elevation	^oC
T9	Thermistor	Ambient elevated above water level	^oC
T10	Thermistor	Glycol into heat exchanger on lid	^oC
T11	Thermistor	Glycol out of heat exchanger on lid	^oC

12.7 Test Procedure

Following construction of the model ice islands, the test package was closed and sealed with the insulating lid. The package was then mounted on centrifuge and all power and instrumentation cables connected. A number of pre-flight checks were undertaken to ensure that all instrumentation was working correctly.

The centrifuge test consisted of two flights. In each flight, the speed was increased in increments of 10g and allowed to stabilize in each stage to ensure that all systems were operating correctly. The first flight was undertaken to allow the ice islands to consolidate and settle under their own increased self-weight as a result of the increased acceleration. The flight was limited to 50 minutes at 100g acceleration. The centrifuge was then spun down and the test package was taken back to the laboratory for inspection and modification.

The measured vertical displacement was measured for both islands using the LVDTs during the first flight as shown in Figure 12.6, with 22 to 23mm being measured. This displacement could be the result of both deformation of the seafloor below the islands and the compression of spray-ice within the islands themselves as well as elastic bending of the beams supporting the LVDTs. The temperature inside of the islands ranged between -0.6 to -1.8°C during the flight, and the temperatures in both the soil bed and water were constant at around -0.5°C.

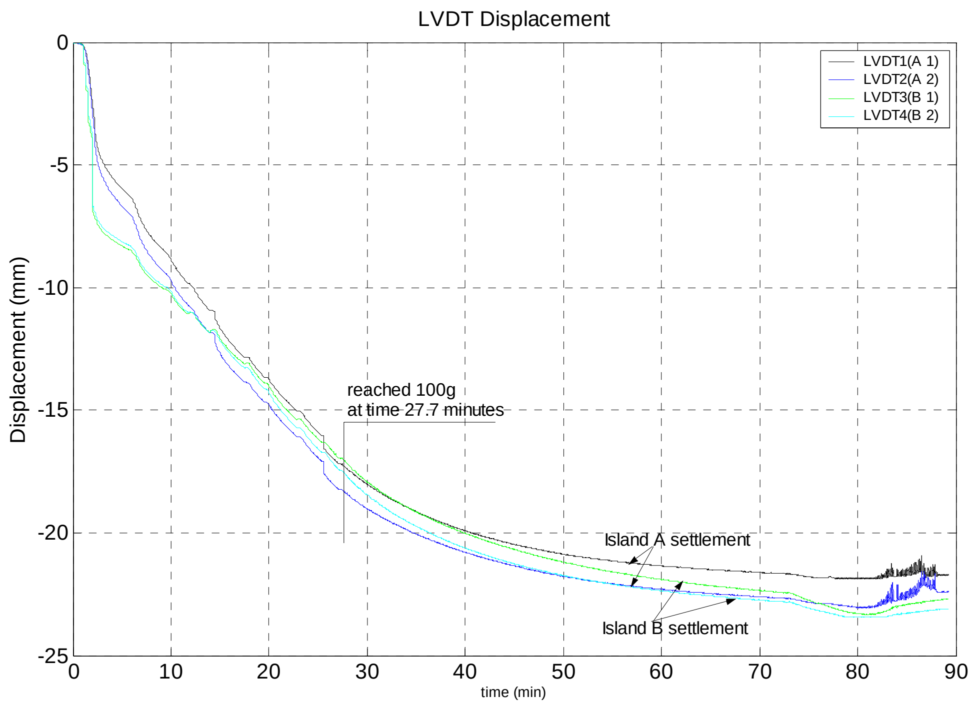

Figure 12.6: Measured Compression of the Islands during First Flight

Following the first flight, additional spray ice was placed on top of the settled islands to rebuild the freeboard to 45mm in height. A dead weight was then applied on each ice island to increase the normal load to simulate the effect of the additional freeboard. The test package was then loaded back on the centrifuge arm and spun up for the second flight. The speed was again increased in increments until it reached the test speed of 100g, to allow for spray-ice settlement.

The air pressure in the pneumatic cylinder was increased in increments to allow gradual build-up of the lateral load applied on the island, which was measured and recorded by the load cell attached under the ram. As the applied load increases and approaches the shear resistance between the island and the sea floor, the islands would have been expected to start to move horizontally due to failure of either the ice/soibed interface or internally within the island. The string potentiometer recorded the vertical movement of the ram, which indicated the horizontal displacements of the islands.

12.8 Test Results

The centrifuge was spun up in increments, reaching the test speed at 16.4 minutes. The pneumatic cylinder ram was activated at a time of 33.3 minutes and the load increased to a maximum value of 1.57kN at a time of 41.7 minutes, at a corresponding displacement of 70mm. A steep reduction in load from 1.57kN to 1kN then occurred between 41.7 minutes and 53 minutes with no further movement recorded by the potentiometer. The ram of the pneumatic cylinder was then lowered to zero. Figures 12.7 to 12.10 present the load cell, string potentiometer, thermistor and pore water pressure data during loading of Island A. The thermistor and PPT data shows that the temperature and water pressures were approximately constant during the test, with no large changes due to external effects.

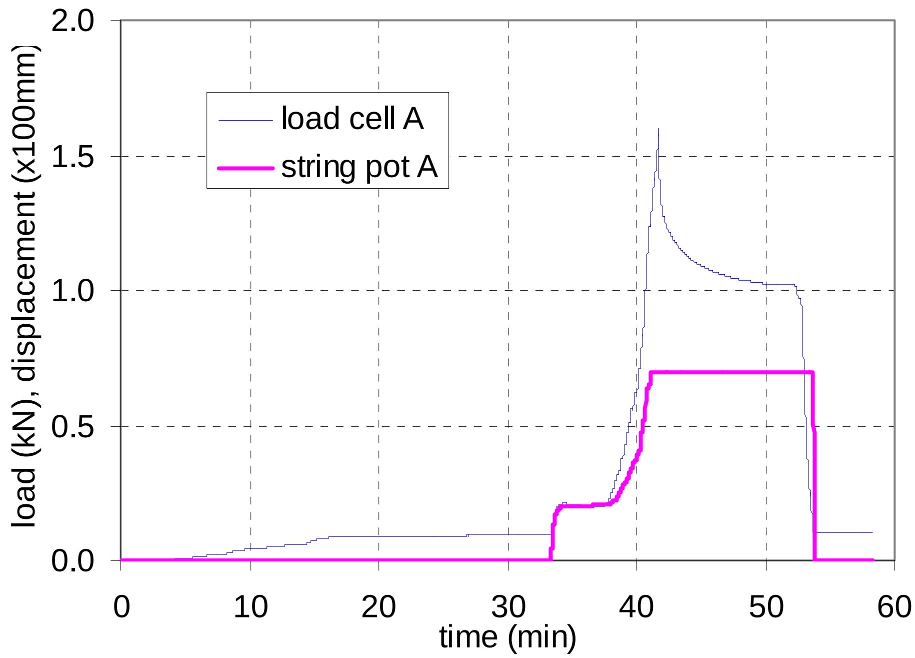

Figure 12.7: Load and Displacement Data, Island A

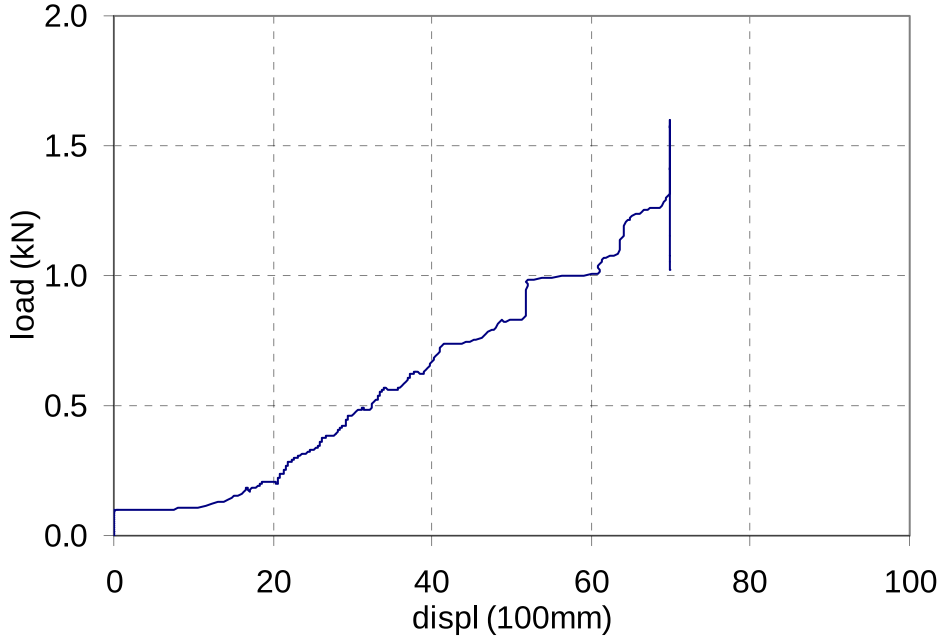

Figure 12.8: Load vs. Displacement, Island A

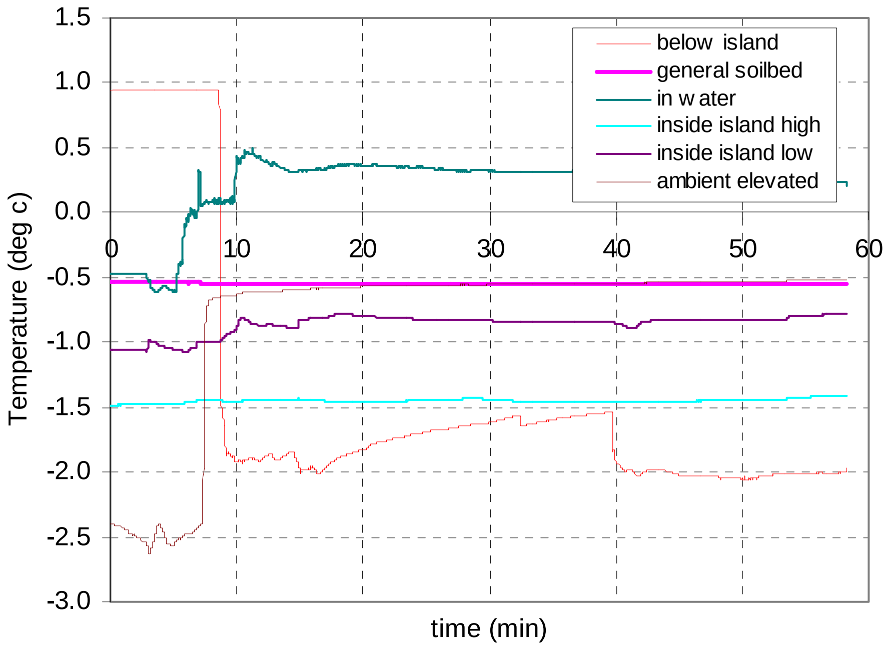

Figure 12.9: Temperature Data, Island A

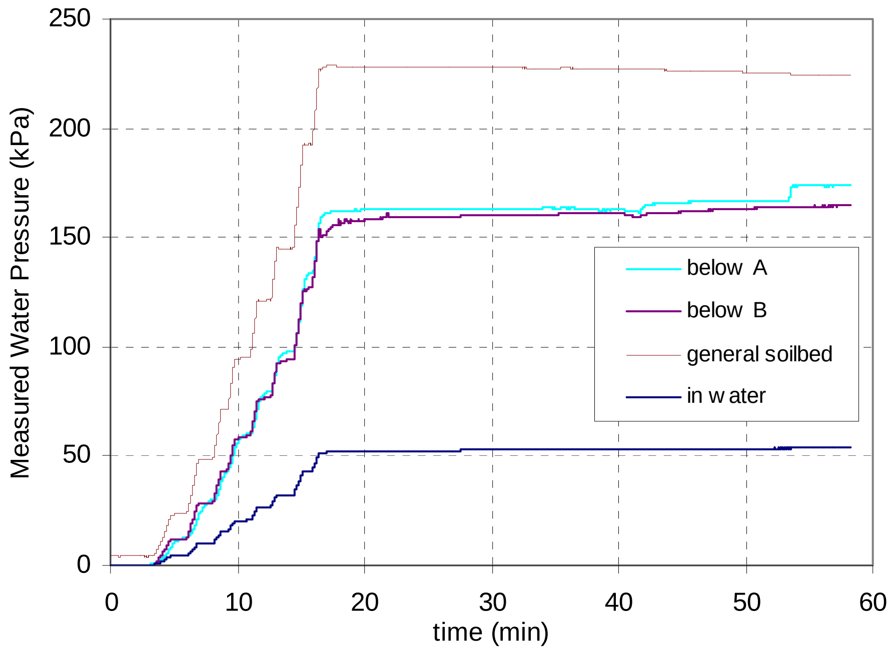

Figure 12.10: Pore Water Pressure Data, Islands A & B

On completion of testing Island A, the pneumatic system was switched to Island B, which was mechanically identical. This was achieved in-flight by switching the plumbing in the centrifuge slip-ring room without interruption of the centrifuge flight. Several attempts were made to pull island B, starting at 61 minutes, without the ability to generate significant displacement. After a number of attempts, the test was abandoned and the centrifuge flight stopped. Post-test observations showed that the signal cable of the string potentiometer had caused the load cell to become stuck in the package lid, which prevented controlled loading of the island. The results of the load cell and potentiometer readings are given in figure 12.11, but do not provide meaningful data for interpretation.

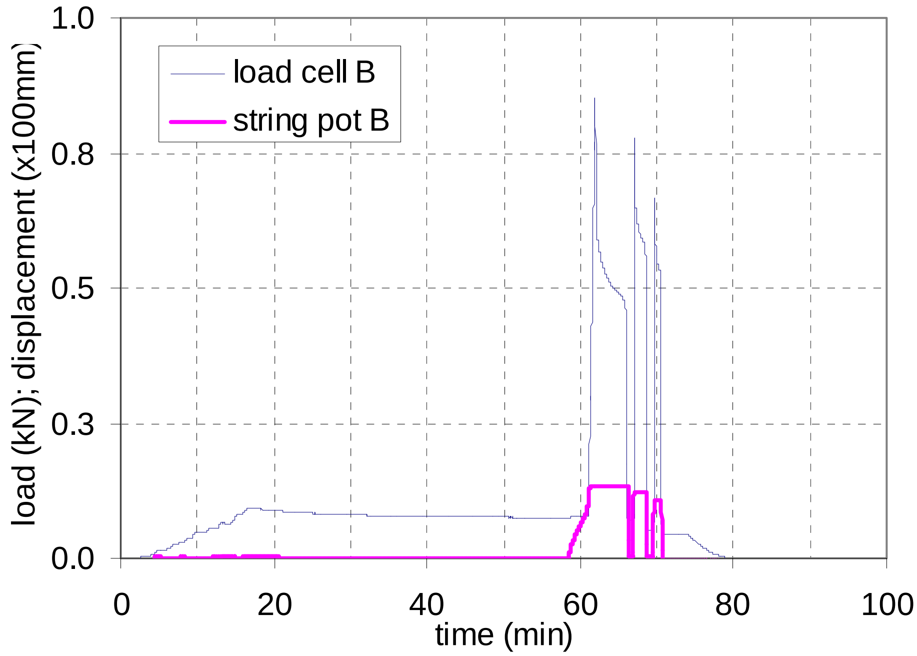

Figure 12.11: Load and Displacement Data, Island B

On completion of the centrifuge test, the water above the soilbed in the test model was drained to allow the model to be observed. Ice was collected from the islands and the resulting density was measured at 720kg/m^3. This is consistent with dry spray ice values presented in Section 6, but lower than typical saturated ice. The loss of pore fluid during the measurement is a possible reason for this lower than expected value.

Observation of the islands and soilbed provided an indication of the island performance during the test. Island A was found to be deformed, with the loading strap having moved towards the centre of the island in the line of action of the load application. The movement was approximately 60mm, close to the measured displacement of the loading cable during the test. A concave shaped footprint was discovered on the soilbed where the island was located at the end of test, with no obvious scouring action from sliding on the seafloor. The maximum depth of the concave footprint was 40mm at the centre. Figure 12.12 shows the island on completion of the test.

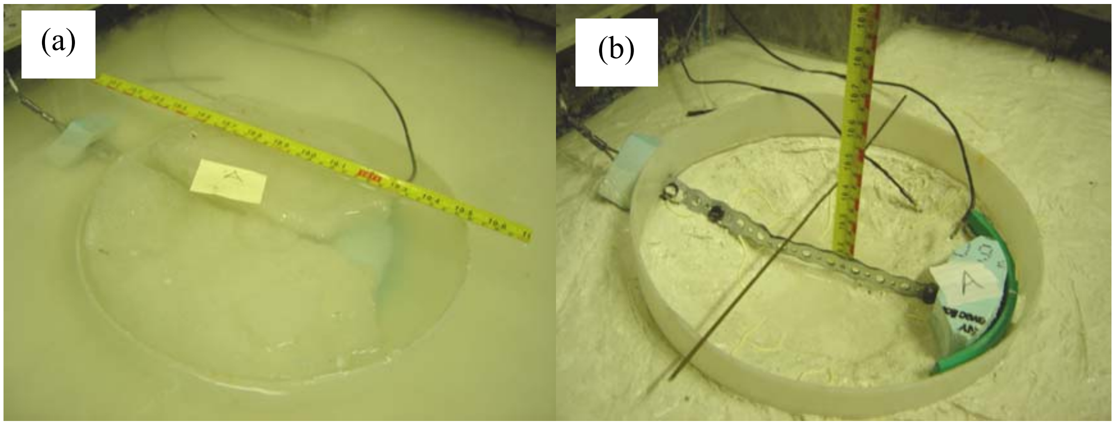

Figure 12.12: Post-test Observation - Island A (a) Directly After Test and (b) After Drainage of water and Removal of Spray Ice

Island B had a rigid plate placed between the ice and the soilbed. The test data showed that the island experienced negligible movement. This was confirmed by observation in that the islands was located at its original location. The rigid plate had created a depression in the soilbed of the order of 25 to 30mm. Figure 12.13 shows Island B on completion of the test.

Hand-Vane shear tests were performed at various locations on the seafloor after the centrifuge test. The average shear strength was 9.5kPa, which is consistent with pre-test values.

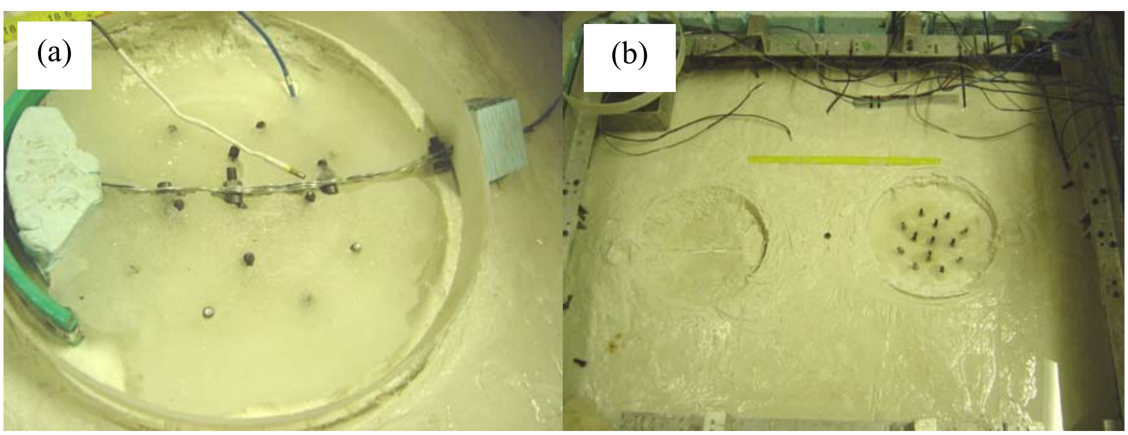

Figure 12.13: Post-test Observation - Island B (a) Directly After Test and (b) After Drainage of water and Removal of Spray Ice

12.9 Discussion

The load test measurements suggest that the peak capacity of the ice island under loading was not reached, as shown by the load / displacement plot given in Figure 12.8. A comparison of predicted load capacity with measured load during the test has been performed using the design principles presented in Section 7. The calculated sliding resistance of the model island is 6175kN at prototype scale using Equation 7.14. This is based on a 30m diameter island, supported on a clay seabed with 9.5kPa undrained shear strength, with a contact factor of 1. This is equivalent to 0.67kN at model scale using standard scaling laws for centrifuge modeling.

Passive edge failure of the island due to loading of the edge strip is calculated at 32.5MN at prototype scale (3.25kN at model scale) using Equation 7.6. This was calculated assuming that the load is applied at sea level for an island with 6m freeboard, and that the width of the loading strip is 12m (scaled form the centrifuge test geometry). A spray ice strength of 120kPa was used. Slightly less than 50% of the calculated capacity is provided by the self weight of the spray ice, with the remainder determined by shear forces within the spray ice body during wedge failure. Therefore, even if the spray ice strength was significantly less than the assumed value, a minimum of 1.5kN would be required at model scale to fail the island core for zero spray ice strength (ie. Greater than double the failure load due to sliding). The passive edge failure calculation is considered conservative, as the loading mechanisms would have initiated failure below water level, resulting in additional weight and length of shear plane for failure. The presence of the loading plate placed on top of the island would also act to increase the failure load by constraining vertical movement of the ice wedge. Since the failure load is proportional to the square of the freeboard, a reduction in island freeboard would reduce the load substantially and may be a reason for lower than expected failure load.

The measured load applied during testing of Island A was 1.57kN, more than double the calculated capacity for sliding along the seabed, and close to the calculated passive edge failure capacity. The observed island condition at the end of the test suggests that failure occurred as movement of the loading strip through the island core, with the plate embedment approximately equal to the measured displacement of the loading cable. No distinct failure wedge was identified, although some build-up of ice was seen ahead of the loading plate that had moved forward. This suggests that some form of edge failure had developed. Further, observation of the final deformed footprint of the island did not indicate any evidence of movement along the soil bed, such as scouring. The depression was that of the circular island geometry. The position of the island after the test was not the same as the pre-test location, the island having moved at some stage during the flight. There is no obvious explanation for this observation. The test data therefore suggests that the sliding resistance of the island was of a greater value than predicted by calculation, although the reason for this cannot be provided based on the test data and observations.

The observed depression in the soil bed due to self weight of the islands was measured at up to 40mm. Based on simple bearing capacity theory, the islands had a factor of safety of greater than 1.3, which would be low for operational conditions, but acceptable for model testing. Elastic compression of the soil bed due to the imposed vertical load of the island is estimated at 4% of the soil thickness, suggesting a settlement of the order of 6mm. This would be increased due to the consolidation of the underlying soil during the length of the centrifuge flight. Consolidation settlement would be expected to contribute another 12mm based on experience in using this type of soil previously in the laboratory.

The performance of the centrifuge test described in this section demonstrates that modeling of ice island type structures is a suitable application of the geotechnical centrifuge. Refinement of the test design and operating procedures would allow more complete simulation of the loading and failure process to determine critical design parameters. The centrifuge has also been used to model ice and investigate ice/structure interaction and failure mechanisms. This is seen as an area of potential development to contribute to improved knowledge related to ice island design and construction issues.

13.0 CONCLUSIONS & FUTURE RESEARCH PRIORITIES

This study has examined the factors that affect the design and construction of ice islands for use as exploration structures in the Beaufort Sea. A review of the development and use of ice islands on an experimental and operational basis provides an insight to the practical challenges that must be overcome. An assessment of ice properties, design criteria and monitoring and maintenance issues all provide the information required to identify the critical factors that must be considered in undertaking such activities. Of particular importance is a careful assessment of ice and other environmental conditions that affect the design requirements and construction capabilities. The mitigation of risk and cost factors is critical to the successful implementation of a drilling program.

The review of historical and current practices for the construction of ice islands has identified a number of areas in which further research and development could provide substantial advantages for offshore exploration operations. These factors that could be developed to optimize the use of ice islands for offshore drilling are identified and discussed in the relevant section throughout the report. The factors that have been determined as priority for potential further development are discussed in this section.

A list has been developed that considers the priority areas in which substantial benefits could be envisaged if current levels of uncertainty were reduced or eliminated. The following issues are considered to be priority areas for future research:

- Ice sheet strength and failure mechanics during interaction with grounded structures. The review of criteria affecting the loads applied to a grounded ice island has demonstrated the sensitivity of crushing strength of the natural first year ice sheet as it interacts with large structures. A wide range of values are presented in existing codes of practice, which suggests that efforts should be directed towards reaching a consensus between the various guidelines to determine the optimum values to use in design. This may require additional testing to fill data gaps, or re-examine existing strength measurement data to establish design criteria. The large width and high aspect ratio of the ice-structure interaction zone of an ice island plays an important role in the loading conditions imposed from the surrounding ice sheet. Rate and stiffness effects of the ice/structure interaction should also be considered. The assessment of failure mechanics suggests that the difference between crushing or passive edge failure is small compared to assumed ice strength, although further work in this area may provide an improved basis for design.

- Sliding resistance of grounded ice islands. There are a number of uncertainties related to calculation of the sliding resistance of a grounded ice island under applied ice loads. Issues such as non-uniform or non-homogeneous strength parameters, effects of embedment of the ice into the seabed and consolidation of clay soils affect the available sliding resistance of a grounded ice island. The centrifuge test demonstrated the potential use of innovative techniques that may be used to determine the relative importance of these parameters, and develop enhanced analysis techniques for use in design. Other physical experiments could also be considered to provide additional information.

- Ice island distortion during loading events. Measurements of island displacement as a result of ice loading on operational grounded ice islands has shown that they do not perform as rigid structures. There is significant distortion of the island, both within the core and at the ice/soil interface, as a result of mobilization of resistance prior to peak load. This has implications on allowable movement at the critical locations such as the conductor. The development of analytical solutions to predict island distortion would allow this behaviour to be considered at design stage.

- Feasibility of construction of ice islands in deeper water environments. Several studies have been reviewed with the aim of extending ice island construction into deeper water whilst maintaining the length of the available drilling season. The conclusion of the studies suggests that construction using existing on-ice techniques is feasible at least up to 12m water depth, and off-ice to significantly greater depth. The potential to use marine demobilization of drilling rigs would allow the drilling season to be extended, which would offer greater flexibility and reduce risk to drilling programs.

- Further study of the deterioration of ice island structures after the winter drilling season. The feasibility of ice island survival to allow multi-year operations has been considered and experimental studies have demonstrated the use of a range of materials that reduce ablation from the surface and erosion from the edge of an ice island. The rate of loss of material during spring and early summer has been quantified, which has allows the size of an island to be calculated that would allow its use on a multi-year basis. Further quantification and assessment of the criteria required for this to be used on an operational basis could significantly reduce costs of multi-year programs should it be successfully implemented. The assessment of additional materials in protecting and reinforcing the island surface may enhance its operational durability.

- Construction management techniques to allow improved feedback of construction related issues to the design. Observational techniques, in which the design allows for monitoring and interpretation of the structural behaviour to adjust the initial construction sequence, has gained acceptance in general construction activities. The nature of construction in an ice environment with a large number of variables, many of which are beyond the control of the team, can be accounted for in the design and construction process. The development of a procedure that feeds into a toolbox to define allowable parameters for use in such a design and operational framework would provide the flexibility to adjust to the actual conditions encountered on site. If successfully used, this could lead to reduced cost and risk to the project.

- Spray ice strength characteristics. The study has shown that the strength of spray ice used in design has a wide range, depending on which data is used as a basis for determining this. Although the strength of the spray ice itself is not usually critical to the ice island design, the establishment of an accepted range of strength characteristics, or methods of preparation that allow more controlled properties would enhance current capabilities. Improved knowledge on strength, stiffness and creep properties of spray ice would then allow it to be used with confidence in structures that are dependent on these properties.

The organization of a forum, with invited participants from industry, regulatory agencies and academic institutions involved in offshore arctic exploration would be a suitable mechanism for disseminating the information contained in this report and for establishing a consensus of opinion regarding future advancements. Although most of the research efforts relating to the use of ice island construction is more than 20 years old, a number of the individuals involved in that work are still active in the industry would be expected to welcome the opportunity to share their experience and help to prepare a platform for future developments.

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