Spray Ice

Prepared for:

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Technology Assessment and Research Branch

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Mr. Charles Smith
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Dear Charles,

Attached is a copy of my invoice for the spray ice report. Bill Mallonee of your purchasing department indicated that you need to sign off on this.

I gave you six copies of version 1.0 of this report at the AROTAC meeting in Anchorage on 30 July. As soon as I receive all of the comments I will provide you with an updated version.

I appreciated being able to produce this report for you. I believe the industry support and cooperation that we received for this work was truly amazing.

Best regards,

Wm. St. Lawrence

William St. Lawrence

Original sent U.S. Mail 11 Aug 92

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LIST OF SYMBOLS

$\dot{\epsilon}$	strain rate
α	contact factor
γ	spray ice weight density
γ'	buoyant weight density
η	porosity
ν	Poisson's ratio
ρ	spray ice density
ρ'	buoyant density of spray ice
ρ_I	solid ice density
ρ_{SAT}	saturated density of spray ice
ρ_{SW}	sea water density
σ	effective pressure
σ_1	minimum principal stress
σ_1'	effective minimum principal stress
σ_3	maximum principal stress
σ_3'	effective maximum principal stress
τ	shear strength
ϕ	friction angle
A'	constant equal to 14.45×10^3
B'	constant equal to 5.40×10^6
c	effective cohesion
d	depth of spray ice below surface
D	island diameter
e	void ratio
E_D	dynamic Young's modulus
F_1	safety factor
g	acceleration due to gravity
h	depth below water
H	island freeboard
h_1	height of spray ice above water
h_2	depth of submerged spray ice and natural ice
I	ice load
m_I	mass if ice
n	ice fraction
p'	effective normal stress
q	effective shear stress
R_A	edge resistance
R_B	internal island resistance
R_D	design ice load
R_S	seabed resistance

t	time
T	temperature
Ta	air temperature
T_F	freezing temperature of water
V_I	volume occupied by ice grains
V_V	volume occupied by voids

METRIC TO USCS CONVERSION FACTORS

To Convert From		To	Multiply By
joule	J	British Thermal Unit (BTU)	9.474 E -04
joule	J	ft lbf	7.376 E -01
joule (kg °K)$^{-1}$	J (kg °K^{-1})	Btu (lbm °F)$^{-1}$	2.388 E -04
kilogram	kg	pound (lbm)	2.205 E 00
kilogram	kg	ton (short, 2000 lbm)	1.102 E -03
kilopascal	kPa	lbf in^{-2}	1.450 E -01
meter	m	yard (yd)	1.094 E 00
meter second^{-1}	m s^{-1}	knot	1.944 E 00
meter	m	foot	3.281 E 00
meter s^{-1}	m s^{-1}	ft s^{-1}	3.281 E 00
meter^2 s^{-1}	m^2 s^{-1}	ft^2 s^{-1}	1.076 E 01
meter^2	m^2	yard^2 (yd^2)	1.196 E 00
meter2	m^2	yard^2 (yd^2)	1.196 E 00
meter^2	m^2	sq ft	1.076 E 01
meter^3	m^3	ft^3	3.532 E 01
meter^3	m^3	yard^3 (yd^3)	1.308 E 00
meter^3	m^3	gallon (U.S. Liquid)	2.642 E 02
meter^3 second^{-1}	m^3 s^{-1}	gallon (U.S. Liquid) min^{-1}	1.585 E 04
newton	N	pound-force (lbf)	2.248 E -01
pascal	Pa	lbf in^{-2}	1.450 E -04
pascal	Pa	foot of water (39.2°F)	3.346 E -04
pascal	Pa	lbf ft^{-2}	2.089 E -02
watt (m °K)$^{-1}$	W (m °K)$^{-1}$	Btu ft (hr ft^2 °F)$^{-1}$	5.778 E -01
watt	W	horsepower (electric)	1.340 E -03
watt	W	ft lbf hr^{-1}	2.655 E 03

1.0 INTRODUCTION

The purpose of this monograph is to consider the current state of technology and developments in spray ice, particularly as it applies to the petroleum industry. To date, two spray ice exploration drilling platforms have been constructed in Canada by Imperial Oil Ltd. (formerly Esso Resources Canada Ltd.) and two have been built in Alaska, one by Amoco Corporation and the other by Chevron U.S.A. Inc. (Table 1.1). In the Canadian Arctic,floating spray ice pads have been constructed to support hydrocarbon exploration in the stable ice of the high Arctic islands (Masterson et al. 1987). There have also been several spray ice barriers to protect drilling and construction operations in ice-covered waters (Jahns et al. 1986, St. Lawrence 1989). Spray Ice has been used for relief pads (Weaver et al. 1991), and there have also been a number of large scale tests conducted to determine how spray ice will perform under simulated conditions.

Table 1.1 Spray Ice Island Summary

Year:	1986	1987	1989	1989
Operator:	Amoco	Imperial	Imperial	Chevron
Name:	Mars	Angasak L-03	Nipterk P-32	Karluk
Location:	U.S. Beaufort Sea	Canada Beaufort Sea	Canada Beaufort Sea	U.S. Beaufort Sea
Water depth:	7.6 m	5.6 m	6.5 m	7.6 m

There are three major advantages in using spray ice platforms for exploration drilling operations. First, they are attractive from an environmental standpoint. Since they are constructed with the local water supply they break up and disappear during the summer melt season. Second, they are less costly to construct and drill from than other platforms, such as concrete structures or dredged sand or hauled-gravel islands. Third, because of their size, and the energy-absorbing properties of spray ice, they are capable of protecting the drilling rig from ice forces which are the major design criterion in the Beaufort Sea.

Recognizing these advantages, the United States Mineral Management Service commissioned this report as a means to compile current information on spray ice, from the diverse and widespread sources of information currently available. To accomplish this we have gathered information from public literature and solicited previously proprietary information from companies who have carried out spray ice operations. In this regard Amoco Corporation, Chevron U.S.A. Inc., Exxon Production Research Company, and Imperial Oil Ltd. have been particularly helpful in providing information on spray ice.

We have compiled this report in a format that will be useful for future spray ice users who may or may not be familiar with spray ice design and construction techniques. To date, most of the published papers addressing large scale operations were written in a case study format. We have synthesized the information from these case histories and arranged it by topic. This strategy should enable the user to readily access the required information to assist in the design process.

It is worth cautioning the reader with regard to the application of the information provided in this report. It may be tempting to extract data and apply it without verification to specific projects. This should not be done. The properties and quality of spray ice vary with the techniques used for fabrication, the environmental conditions under which it is made and the postconstruction environment. In constructing with spray ice site specific planning must be carried out to assure that the spray ice structure is compatible with a wide range of environmental parameters including temperature, ice forces and the overall operating environment.

Throughout ice construction the quality of the spray ice must be monitored to assure that it meets design standards. For instance, changes in temperature at which the spray ice is formed can greatly effect the density of above water spray ice. This in turn will effect the integrity of the spray ice structure. Also, after completion of any spray ice structure and before operations begin, a careful postconstruction monitoring program must be carried out to assure the initial design requirements are satisfied. Again, due to the fact that unlike many construction material the quality of spray ice, especially the unsaturated ice above sea level, can be highly variable depending on the conditions under which it was formed. During the active operational life of the structure a postconstruction monitoring program will most likely be required. The extent of this program will be dictated largely by operating conditions and site specific environmental conditions.

In this monograph we consider the factors required for constructing an offshore exploration drilling pad made by grounding spray ice. We start by considering the physical process of spraying water into the air to obtain the basic construction material. We then consider what is known of the physical and mechanical properties of spray ice considering such factors as density, strength and creep characteristics. Consideration is given to the equipment used for constructing a spray ice island and the site specific requirements such as location and operating season. In Chapter 11 we look at some extended operations on spray ice both in terms of what has already been tried and where future spray ice operations may lead.

2.0 SPRAY ICE FORMATION

2.1 Spray Ice Formation

As its name suggests spray ice (or alternatively sprayed ice) is made by spraying a stream (or multiple streams) of water into the air in subfreezing temperatures. After leaving the nozzle, the stream breaks up into individual particles and depending on temperature and other factors, some fraction of the water freezes as it falls. In most instances some unfrozen water reaches the ground and freezes or drains away. If sea water is being pumped, brine will be rejected during the freezing process and will eventually drain. As spraying continues a mass of granular ice is accumulated which becomes the foundation of the spray ice structure.

Spray ice is a term introduced by the oil industry. Prodanovic (1986) refers to ice made by spraying on a manmade ice island constructed in the winter of 1978/79 and Neth et al. (1983) refer to "spray flooding" as one of the techniques used in constructing a relief ice pad. Collins and Masterson (1989) put a wider perspective on spray ice by considering it as a variant of the snow making techniques used by the ski industry.

For our purposes we will consider spray ice to be a high density form of snow ($\approx$600 kg m^{-3}) made by spraying water into below freezing air.

The practical application of spray ice has preceded the theory on how spray ice is formed and how atmospheric factors effect its formation. Szilder et al. (1991) describe spray ice formation as a process of heat exchange between the water droplets forming the spray stream and the cold air.

The stream of water breaks into droplets, which become supercooled when their temperatures fall below the freezing point. Freezing takes place when the temperature of the droplet reaches the nucleation temperature. The nucleation temperature is a function of the droplet size, the cooling rate and the type and concentration of freezing nuclei. Using data from Hobbs (1974) we can estimate the nucleation temperature for a 3 mm water droplet to be -20°C. When the nucleation temperature of the droplet is reached a rapid freezing of some of the water in the droplet takes place as sensible heat is transferred into latent heat. The temperature of the droplet during this phase increases to the freezing temperature. With a portion of the droplet frozen, additional ice is formed at the freezing point. Szilder et al. (1991) note that the heat exchange process when the droplet is at the freezing point is more efficient than during the super-cooled stage because of the greater temperature differential between the droplet and the air.

It has been observed that spray ice manufacturing efficiency decreases significantly (Jahns et al. 1986, Bugno et al. 1990) above temperatures of -20°C. The higher the temperature the lower the ice fraction of the falling stream. Szilder et al. (1991) present an analytic relation for the ice fraction for temperatures less than -20°C based on a graphical representation of data presented by Masterson (1990). The equation Szilder et al. (1991) present suggest that the ice fraction in percent can be described by:

$$n = 0.4(T_f - T_a)t \qquad (2.1)$$

where:
- n is the ice fraction in %
- T_f is the freezing temperature of water (°C)
- T_a is the air temperature (°C)
- t is the fall time of the droplet(s)

Note that Eq. 2.1 has no physical meaning beyond 250 degree seconds. It is also not likely that the ice fraction, for sea water, will ever reach 100% under most atmospheric conditions.

For temperatures above -20°C Szilder et al. (1991) suggest that spray ice production is low because most of the droplets do not freeze. In air temperatures above -20°C the droplets super-cool but do not change phase. In this case as the water impacts the surface the sensible heat deficit of the super-cooled droplets is transformed to latent heat and a portion of the water freezes. The fraction of water that freezes on impact increases with the hang time of the droplet in the air.

Allyn and Masterson (1989) present a fairly complete model for both the formation of ice from the spray stream and ice growth from free water landing on the surface. They integrate this information into a global model to predict the overall build up with time of a spray ice island. In their work they present the governing equations for the water jet trajectory, which is important for considering the formation of ice particles from a water stream.

In spray ice operations the water typically leaves the nozzle at an exit velocity which is a function of the flow rate and is functionally related to the nozzle outlet diameter. The water stream remains intact until a critical velocity is reached, at which point the water stream breaks up into droplets.

Allyn and Masterson (1989) note that nozzle exit velocities of 50 m s^{-1} are desirable. From observations they found that the critical velocity at which the stream breaks up appears to be approximately 14 m s^{-1} and droplet diameters are typically on the order of 3 mm. Imperial Oil Ltd. performed full-scale tests and found average droplet diameters of 1.5 to 2.0 mm.

In offshore operations the water pumped to produce spray ice is sea water with salinity ranging from 25-35 parts per thousand (ppt). However, depending on the proximity of the construction site to freshwater river channels, the water can have much lower salinity or even be fresh water as was the case for the Nipterk Spray Ice Island constructed in the mouth of the Mackenzie River. Allyn and Masterson (1989) make the assumption that "the ice formed as the droplet cools is essentially freshwater ice." This assumption would appear justified in light of U.S. Patent US4592768-A (1986). In this patent potable water is recovered from brine which is passed through a freeze exchanger to form an ice slurry. The solid ice particles are then separated from the slurry and melted to recover the potable water. Evidence that spray ice is essentially fresh water ice becomes important when we discuss the physical properties of spray ice.

The papers by Allyn and Masterson (1989) and Szilder et al. (1991) represent the most currently published theories of spray ice formation. There are a number of reports in the literature on field observations regarding the formation and spray ice. Jahns et al. (1986) noted that in calm conditions nozzle elevation angles of 60° gave optimum results for the formation of spray ice with droplet hang times of 10 seconds. With winds less than 8 m s^{-1} (≈16 kts) nozzle elevations of 45° to 60° were used. When the wind was greater than 8 m s^{-1} (≈16 kts) the spray stream was directed across the wind flow and nozzle elevations of 35° to 45° were used.

It should be noted that the data presented by Jahns et al. (1986) was for water monitors mounted 15 m above sea level and in part accounts for droplet hang times of 10 seconds. Hang times of three to four seconds may be more typical of monitors mounted at sea level (Szidler et al. 1991).

Information presented by Collins and Masterson (1989) agrees with the data presented by Jahns et al. (1986). Collins and Masterson (1989) state that the most effective angle for cooling the spray stream is between 40° and 75°.

In terms of nozzles used for spray ice construction Weaver et al. (1991) notes that straight stream fire nozzles produce optimal results. Weaver et al. (1991) defines spray ice efficiency as the fraction of water that freezes to the amount that is pumped. Weaver notes that the spray ice efficiency is a function of the air temperature, the pump and nozzle characteristics and the salinity of the water being pumped.

2.2 Summary

1. For standard spray ice operations to be viable the temperatures must be below -20°C and the winds less than 10 m s^{-1} (20 kts).

2. The most important factor in cooling the water in the spray ice stream is the hang time of the water droplet.

3. For conventional nozzles, elevations from 40° to 60° above the horizontal produce the best results in spray ice operations.

4. When winds exceed 8 m s^{-1} ($\approx$16 kts) much of the spray stream may not land in the target area. To keep the spray in the targeted area the nozzle elevation angle can be lowered. However, lowering the nozzle elevation angle reduces the hang time of the droplets.

of free water. However, shortly after the temperature of the ice mass drops below freezing grain bonds grow through the process of sintering. The primary strength of spray ice is derived from the growth of grain bonds due to the sintering process.

Little or no data exist on the physical processes that take place in spray ice that is below the surface of the water. Observations by Chen and Gram (1989) indicate that the mechanical properties of the above- and below- water properties of spray ice do not vary widely. Structural comparison of above- and below- water spray ice samples also show little difference macroscopic structural characteristics.

The mechanical behavior of submerged spray ice may in part be described by the mechanisms described by Colbeck (1978a). However, when spray ice is submerged in sea water the temperature of the sea water is below the melting point of the ice particles. This suggests that the sintering process that acts in the cold above-water spray ice may also take place in the submerged ice. We know from observation, that both cohesionless and cohesive spray ice exist below water.

Important observations of snow in water have been made by Wakahama (1968) and also by Colbeck (1978a). The results of their research shows that for snow immersed in water, a general coarsening of the grains takes place. Figure 3.1 taken from Colbeck (1978a) shows the redistribution of grain size in water- saturated snow over a six-day period, Colbeck's work implies that for submerged spray ice the structure of the initially immersed material will bear little resemblance to the final product.

Although there is an overall lack of information on saturated snow and its behavior, there is a large body of information on the properties and processes that take place in cold dry snow. There is also a large volume of information available on methods used for construction with dry snow. See for example Investigation and Exploitation of Snowfield Sites, (Mellor, 1969a) and Snow Roads and Runways, (Abele, 1990).

In dry snow, there is an absence of liquid water. Snow is considered a composite material comprised of water vapor, air, and ice grains. Snow (and spray ice) is an interesting material in that it undergoes metamorphism, or change of character, which brings it into equilibrium with its thermodynamic environment. Mellor (1964, 1969a, 1969b, 1974) has written extensive reviews of the properties of snow, particularly those properties in the density range of interest in construction with spray ice (i.e. 500-700 kg m^{-3}).

At temperatures below freezing ice grains change their shape and size by sublimation. During the sublimation process changes take place in the mass of ice grains due to local differences in vapor pressure. Water molecules evaporate from areas of high vapor pressure and are deposited in areas with low vapor pressure. That is, grains with small radii or sharp corners have a higher vapor pressure than larger rounded grains. Thus small grains give up mass to larger grains.

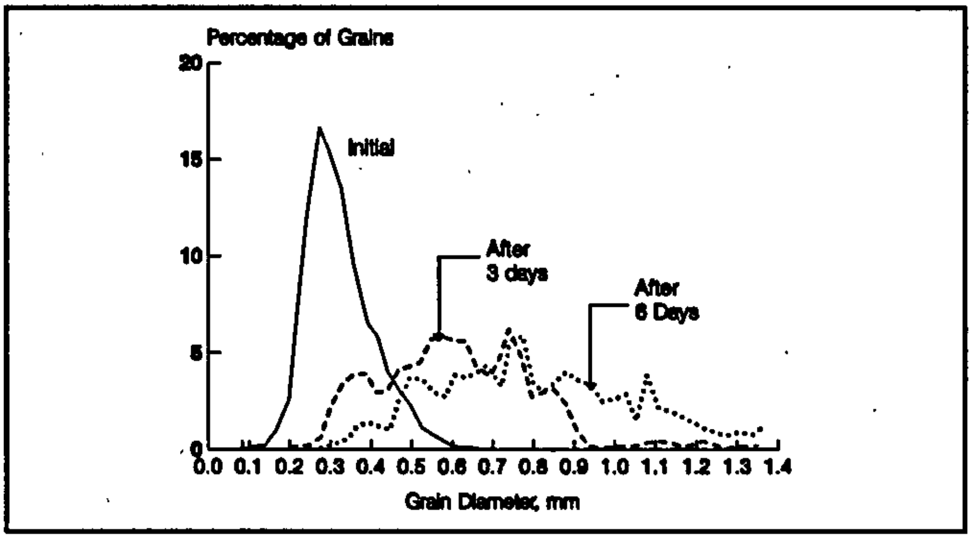


Figure 3.1 Distribution of snow grains initially; immersed in water for three days and for six days. From Wakahama (1969) and Colbeck (1978a)

After a period of time the ice grains comprising the snow or spray ice tend toward equilibrium in their size and shape. This accounts for the uniformity of ice grains observed in spray ice structures.

In addition to sublimation which forces the ice grains into thermal equilibrium, sintering takes place between grains resulting in the growth of grain bonds. Sintering is the process by which grain bond formation takes place as a result of diffusional processes. Grain bond growth represents an energy expenditure which causes the surface energy of the grains to become equipotential. Grain bond growth takes place in the absence of liquid water and at relatively rapid rates. Figure 3.2 adapted from a presentation by Mellor (1964) depicts the formation of grain bonds between ice grains immersed in kerosine at -3.5°C. One can see in Figure 3.2 that recognizable grain bond growth is visible 35 minutes after the grains come into contact. After 1369, minutes substantial bond growth has taken place.

The formation of grain bonds by diffusional processes accounts for the strength of spray ice. Initially, freezing of liquid water in the spray ice may provide some strength. However, the spray ice derives its primary strength through grain bond formation due to sintering.

When we consider the mechanical behavior of spray ice, especially its creep and strength properties, we need to consider the structural changes due to sublimation,vapor deposition and sintering that take place in the material. Until the spray ice comes to equilibrium with its thermal environment significant changes take place in its structure. During this period of stuctural readjustment its mechanical properties change dramatically. In construction with cold dry polar snow (for example, runways in Antarctica) it is recognized that a period of material curing is

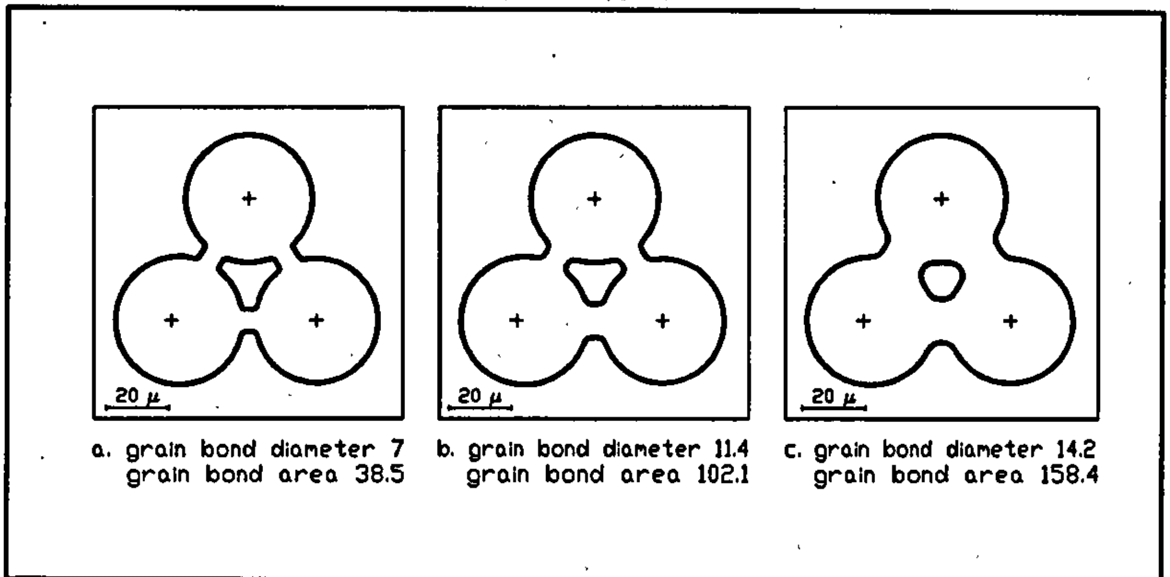


Figure 3.2 Growth of ice bonds between three ice spheres immersed in kerosine at -3.5°C: (a) after 35 min in contact, (b) 279 min. (c) 1369 min.

required. This curing time is generally referred to as the age hardening process. Mellor (1964) presents a succinct discussion of bonding and age hardening in snow.

Figure 3.3, taken from Nakaya illustrates the effect of grain bond growth (age hardening) on the properties of snow. This shows the change in the dynamic Young's modulus as age hardening takes place.

3.2 Mechanical Properties

The difficulty encountered in attempting to characterize the mechanical behavior of spray ice or snow has been pointed out by Mellor (1974). He indicated that as long as the bulk stress remains below a certain critical value the deformation of snow can be treated as a low compressible solid. However, when the critical value is exceeded, snow undergoes large irreversible volumetric strains which cause it to acquire significantly different mechanical properties. In considering the mechanical properties of snow this must be kept in mind. For most engineering problems the body forces (gravity forces) are low enough so that the critical stress value is not exceeded.

3.2.1 Density and Related Properties

An important parameter in defining the properties of spray ice is density. Density is functionally related to the strength of spray ice and also is a critical parameter when calculating the sliding resistance of spray ice structures to ice loads. The bulk density of snow is defined in terms of mass per unit volume. For our purposes we will us the units kg m^{-3}.

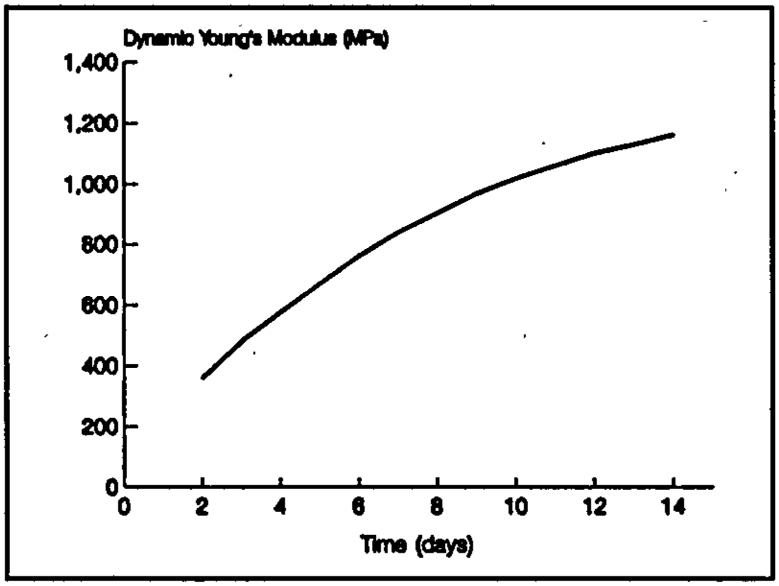


Figure 3.3 Dynamic Young's modulus as a function of time during the period of intergranular bond formation.

Density is defined by the equation:

$$\rho = m_i/(V_i + V_v) \qquad (3.1)$$

where:
- ρ is the density of spray ice (kg m^{-3})
- m_i is the mass of ice
- V_i is the volume occupied by the ice grains
- V_v is the volume occupied by voids between ice grains

To measure the density of spray ice a known volume of spray ice is weighed.

A property related to density is porosity. Porosity is defined as the ratio of void volume to the total volume. Porosity (η) is defined by the equation:

$$\eta = V_v/(V_i + V_v) \qquad (3.2)$$

Eq. 3.2 can alternatively be expressed as:

$$\eta = (\rho_i - \rho)/\rho_i \qquad (3.3)$$

where:
- η is the porosity
- ρ_i is the density of solid ice (kg m^{-3})

Below-water spray ice densities have been reported in terms of the both saturated density and the buoyant density. For example, Chen and Gram (1989) reported the density of submerged spray ice at the Orion Site as ranging from 820 to 920 kg m^{-3}. Alternatively Weaver and Gregor (1988) reported a below-water density of -100 kg m^{-3}. Chen and Gram reported the saturated density and Weaver and Gregor reported the buoyant density. For our purposes we will use the definition of the buoyant density for submerged spray ice. The buoyant density is defined as:

$$\rho' = \rho_{SAT} - \rho_{SW} \qquad (3.8)$$

where:
- ρ' is the buoyant density of spray ice
- ρ_{SAT} is the saturated density of spray ice
- ρ_{SW} is the density of sea water

It should be noted in Eq. 3.8 that the buoyant density of spray ice is negative. This has an important consequence in calculating the amount of overburden required to resist ice loads. The effective overburden pressure on a spray ice island increases linearly with depth to sea level and then decreases with depth below sea level.

The buoyant density of spray ice has been derived from large-scale observations (Jahns et al. 1986) to be -120 kg m^{-3}. Table 3.2 provides the buoyant density reported for three specific locations.

It should be noted that as spray ice is submerged, sea water enters the pore space between grains. However, saturation is not total and air remains trapped in the intersticial space. Results from tests from the Nipterk Spray Ice Island (Imperial 1991) indicated that the degree to which the submerged ice was saturated was 93%.

Table 3.2 Buoyant density of spray ice

SITE	DATE	DENSITY (kg/m3)	REFERENCE
Exxon Antares Barrier	1984/85	-120	Jahns et al. 1986
Imperial Angasak Island	1986-87	-100	Weaver and Gregor 1988
Imperial Nipterk Island	1988/89	-90	Imperial 1991

3.2.2 Quasi-Elastic Properties

Spray ice, like snow is a viscoelastic or viscoplastic material. As suggested by Mellor, (1964) for low stresses (i.e. stresses below 54 kPa) high density snow (and spray ice) can be modeled as a linear viscoelastic material. For high stresses snow is a highly non-linear material.

Under some design circumstances it is necessary to define the elastic properties. In terms of dynamic loads, a significant amount of data have been accumulated for polar snow. This information is primarily derived from seismic surveys conducted on the polar ice sheets.

Young's Modulus

For age hardened dry snow at temperatures of -10°C,in a density range of 500 to 800 kg m^{-3} the dynamic Young's modulus is represented by the following equation developed from graphical data presented by Mellor (1964):

$$E_d = A'\rho - B' \qquad (3.9)$$

where:

- E_d is the dynamic Young's modulus in kPa
- ρ is the density of spray ice in kg m^{-3}
- A' is a constant equal to 14.45×10^3 (m)
- B' is a constant equal to 5.40×10^6 (kPa)

It should be noted that Eq. 3.9 presents the dynamic Young's modulus for snow at -10°C. Nakaya (1959) has shown that there is some degradation in the dynamic Young's modulus at higher temperatures. Nakaya measured the dynamic Young's modulus for snow at -2°C at 2.5 x 10^3 MPa and at -10°C at 3.1 x 10^3 MPa. Considering Nakaya's data the dynamic Young's modulus appears to vary in a linear manner over this temperature range.

The dynamic Young's modulus is for snow subjected to high rates of loading and with small elastic strains. The dynamic modulus values should only be applied to problems where high rates of loading take place. Calculating stresses that result from wheel loads is an example.

For lower rates of loading there appears to be a significant degradation in the apparent Young's modulus. When the tangent modulus from quasi-static tests is used, the apparent Young's modulus appears to be several orders of magnitude less than the dynamic modulus. Lee et al. (1989) reported the apparent Young's modulus for age hardened Antarctic snow with a density of 532 Kg m^{-3} tested at a temperature of -14°C to range between 40 MPa and 55 MPa. For the analysis of Amoco's Mars Island, Vinogradov and Masterson (1989) report using values of 1000 MPa for above-water spray ice and 110 MPa and 70 MPa for below-water spray ice. Presumably the 110 MPa value is for strongly bonded submerged spray ice and the 70 MPa value is used to represent weakly-bonded submerged spray ice.

Overall, there is a lack of data available regarding the moduli values of above- and below-water spray ice subjected to quasi-static loadings. The interpretation of the meaning of these values can also be called into question. An elastic modulus value is most often interpreted to be related to the spring constants in the phenomenological models of snow that are sometimes used.

Poisson's Ratio

A number of experiments have been carried out to determine Poisson's ratio for snow. Typically values near 0.3 are used for Poisson's ratio for small strains. Bentley et al. (1957) provides the following equation for the value of Poisson's ratio for dry snow in a density range from 400 to 700 kg m^{-3}:

$$\nu = (1.5x10^{-4})\rho + 0.2 \qquad (3.10)$$

where: ν is Poisson's ratio
ρ is the density of spray ice (kg m^{-3})

3.3 Creep Properties

From the standpoint of spray ice design and construction,spray ice creep properties are more important than elastic properties. In spray ice islands creep is exhibited in terms of the long-term island settlement. Considering that the movement tolerances of the well and drilling equipment are typically less than a few tens of centimeters, the design of spray ice structures will usually be controlled by creep rather than elastic strength properties. The creep settlement of spray ice islands can be considered in terms of two mechanisms.

During the construction of the spray ice island and for a short time afterward the island exhibits rapid settlement. After the period of relatively rapid settlement the creep or settlement rate decreases. The initial phase of settlement is due to grain bond growth and to decay and rearrangement of the ice grains. In general, structural changes in the spray ice take place when it comes into equilibrium with the thermal environment. For wet snow Colbeck (1978a) demonstrated that power law creep played a small role in the deformation of snow and Mellor (1974) considers the initial rapid settlement of dry snow in terms of a "quasi-plastic collapse" of the structure.

As the island ages settlement rate decreases. This phase may be dominated by law creep although creep due to structural rearrangement must also play some role since the thermal environment changes with the season.

There are some published data (Weaver and McKeon 1986, Shields et al. 1989) on the creep of snow from laboratory experiments. However, it is difficult to make a correlation between laboratory creep data and observations of creep settlement on spray ice islands.

Several investigations have been carried out on the long-term settlement of spray ice barriers, test structures and islands. When deformation data reported in the literature is normalized in terms of strain and strain rate the results are consistent from structure to structure.

Jahns et al. (1986) reported settlement rates of 0.61 m to 0.76 m per month at the CIDS Antares site for the first one to two months with the settlement rate decreasing to 0.3 m per month thereafter. The measurement program took place from December 1984 until June 1985. Initially strains of 1.8% per month were recorded, these reduced to 0.9% per month later in the season. Using this information, settlement strain rates on the order of 10^{-9} s^{-1} are calculated.

Chen and Gram (1989) reported on the deformation of the spray ice test structure built at the Orion site during 1986. When there deformation data are normalized to their study site elevation the total strain over their 84-day observation period was 4%. This also indicates an overall strain rate of 10^{-9} s^{-1}.

Chen and Gram (1989) also reported the results of settlement gauge measurements at the Orion site. Between 21 March and 21 May 1986 settlement gages measured 0.67 m of settlement, representing a total strain of 2.3% and again producing a strain rate on the order of 10^{-9} s^{-1}. The strain in the submerged spray ice was measured to be about-twice the strain in the above-water spray ice.

At Amoco's Mars Island settlement, of the rig substructure was measured between 16 March and 18 April 1986. The maximum settlement measured was 174 cm. the total strain was 1.14% and the overall strain rate was 4×10^{-9} s^{-1} (Amoco 1986).

Weaver and Gregor (1988) reported the vertical settlement at the Angasak Spray Ice Island ranged between 0.15 m and 0.2 m from 5 Feb to 20 April 1987. Using and average value of 0.175 m indicates the total vertical strain for this period was 1.5%. This indicates an average strain rate again on the order of 10^{-9} s^{-1}.

Settlement data derived from measurements made near the rig foundation on Karluk Island, 23 February to 28 March, 1989 were reported by Bugno et al. (1990). The total deformation was reported to be 0.127 m resulting in a total strain of 0.9%.The average strain rate for this period was on the order of 10^{-9} s^{-1}. From the data presented it appears that the above-water strain rates were slightly higher than the below-water strain rates.

Settlement data from Imperial Oil's Nipterk island produced similar results. The average settlement from five settlement gauges over a 112 day period in 1989 showed a total island settlement of 0.21 m. The nominal strain was 1.9% and the average strain rate was about 10^{-9}

per second. The vertical strain above- and below-water was 1.3% and 1.9% respectively over this time period.

The strain rate data from the above observations is summarized in Table 3.3

Considering Table 3.3 it appears that the observed strain rates between the structures compared do not vary widely. However, the Exxon test structures do show higher creep rates than the other islands. It is of interest to note that the Amoco and Chevron data do not show significantly higher rates even though the settlement gauges were in the vicinity of the drilling unit. This might be expected since the weight of the drilling units is small compared to the weight of the spray ice.

We have not tried to correlate observed large-scale creep data with laboratory data. There appears to be some discrepancy between laboratory creep data and field observations. One aspect of the creep of snow which has been noted by Mellor (1974) and is stated by Shields et al. (1990) is that "There appears to be a threshold stress level below which strain rates are independent of stress."

Table 3.3 Vertical strain rate x 10^9 s^{-1}

SITE	OVERALL STRAIN RATE	STRAIN RATE SATURATED	STRAIN RATE UNSATURATED
Exxon Antares Barrier	3.4 - 8.5	***	***
Amoco Mars Island	4.0	***	***
Exxon Orion Experiment	4.4 - 5.5	2.9	1.5
Imperial Angasak Island	2.3	***	***
Chevron Karluk Island	3.2	3.3	3.9
Imperial Nipterk Island	2.0	1.4	2.0

*** data not available

3.4 Failure Criteria

The failure of spray ice is not well defined. In the American Arctic it has been the practice to use a modified Mohr-Coulomb failure model. In recent developments by Imperial Oil Ltd. a more realistic model that incorporates the important parameters of temperature, strain rate and the geometric structure has been used. We will review both approaches here.

3.4.1 Mohr-Coulomb Failure Model

As pointed out by Mellor (1974) the failure of engineering materials is somewhat arbitrary and is primarily a function of when the material performance ceases to be satisfactory. In snow at high rates of loading the snow structure can become disaggregated. At lower rates snow will creep; if the creep rate becomes excessive then this can be considered the limiting material property. This is the governing factor when considering the time-dependent settlement of a spray ice island subject to working loads. In terms of loads imposed, the failure point may be considered as the onset of secondary creep in the stress strain curve.

The Mohr-Coulomb failure criteria can be stated in terms of the equation:

$$\tau = c + \sigma \tan\phi \qquad (3.11)$$

where:
- τ is the shear strength (kPa)
- c is the effective cohesion (kPa)
- σ is the confining pressure (kPa)
- ϕ is the effective friction angle

Mellor (1974) considers the physical meaning of each of the factors in Eq 3.11 and also points out that the Mohr-Coulomb criteria may be of limited value in dealing with snow. For snow the cohesion constant (c) can be considered related to the intergranular bonding of the snow and as such would be dependent on the rate of loading, and the temperature of the material and its structure. The friction angle ϕ is related to the initial strength of disaggregated snow or the strength after the bonds have been broken.

In terms of snow or spray ice there are serious drawbacks in applying Eq. 3.11. Again as pointed out by Mellor(1974), "it is questionable whether internal friction can be fully mobilized until c is effectively destroyed, either by deviatoric stress or bulk stress (σ), and there is no doubt that in some cases σ, or the bulk stress, completely changes the state of the material, thereby vitiating the concept."

For dry snow at the temperatures which are encountered in spray ice islands it is doubtful whether the Mohr-Coulomb model has any meaning at all in terms of physical processes. For saturated, weakly bonded snow a case can be made in physical terms for the Mohr-Coulomb model.

We can examine the failure of snow in terms of the Mohr-Coulomb model from data presented by Chen and Gram (1989). Chen and Gram carried out a number of triaxial tests on spray ice and interpreted their results in an effective stress model. In this model the failure envelope is presented in terms of the effective shear stress and the mean normal effective stress. These values are defined by the equations:

$$q = (\sigma_1 - \sigma_3)/2 \quad (3.12)$$

and

$$p' = (\sigma_{1'} + \sigma_3')/2 \quad (3.12)$$

where:

- q is the effective shear stress
- p' is the effective normal stress
- σ_1 is the minimum principal stress
- σ_3 is the maximum principal stress
- σ_1' is the effective minimum principal stress
- σ_3' is the effective maximum principal stress

The terms σ_1', σ_3' are defined as:

$$\sigma_1' = \sigma_1 + u \quad (3.13)$$

$$\sigma_3' = \sigma_3 + u \quad (3.14)$$

and

$$u = \gamma' h \quad (3.15)$$

where:

$$\gamma' = \rho' g \quad (3.16)$$

- ρ' is defined by Eq 3.8 as $\rho' = \rho_{sat} - \rho_{sw}$
- h is the depth below water (m)
- g is the acceleration due to gravity (9.8 m s^{-2})

Note that Eq. 3.12 can be written as

$$p' = p + u \quad (3.17)$$

where:

$$p' = (\sigma_1 + \sigma_3)/2 \quad (3.18)$$

Note: In soil mechanics it is common to take compressive stresses as negative. For unsaturated spray ice u is equal to zero.

It is convention to define failure in this model as the maximum (q/p') value. Chen and Gram (1989) found that the saturated spray ice fitted the effective stress model well. However, for the above-water spray ice the definition of failure was modified. Here the definition of failure was taken as the creep yield point on the stress strain curve. When this definition of failure for the above-water samples was used the data appeared to fit the failure criteria.

In terms of the Mohr-Coulomb failure model,

$$\tau = c + \sigma \tan\phi \tag{3.11}$$

The value of c and ϕ derived from the Chen and Gram data are

$$c = 11.5 \text{ Kpa}$$

and

$$\phi = 51.5°$$

For the samples tested by Chen and Gram the shear strengths of the above-water ice ranged from 190 to 380 kPa with the strength varying linearly with overburden pressure (depth). The strength of bonded below-water ice ranged from 170 to 310 kPa; for the unbonded below-water samples the strength ranged from 95 to 170 kPa. The below-water samples did not show any pattern of increasing strength with depth.

The authors note that the stress-strain behavior of spray ice did not show any great variation with confining pressure, strain rate or temperature in the range tested.

In view of the fact that spray ice as it is used for ice pad construction is formed and matures under similar conditions and its internal structure is similar from site to site, it is possible to rationalize the failure data offered by Chen and Gram as sufficient when considering spray ice island design.

For Karluk Island a modified Mohr-Coulomb model was employed. For the above water spray ice the failure shear strength was assumed to be constant at 146 kPa. For the submerged spray ice the value of the effective cohesion factor (c) was taken at 19.2 kPa and the friction angle (ϕ) was taken as 30°.

Imperial Oil Ltd. has produced a failure model that integrates explicitly the factors of void ratio, strain rate and temperature.

3.4.2 Imperial Failure Model

The Imperial Oil strength model addresses the ductile failure of spray ice. The point of failure is defined as the creep inflection point in the stress-strain curve. The model is valid for saturated and unsaturated spray ice that has been aged and cured under a minimum stress of 10 kPa and is failed at strain rates less than 10^{-3} s^{-1}.

The stress-strain curve for spray ice subjected to triaxial loads is approximately bilinear. In the initial phase of the test the stress rises rapidly. At the "yield point" the rate of stress increase decays rapidly and further straining results in much smaller increase in stress. The yield point separates these two regions and usually occurs at strains of 0.2% to 0.5%.

It is assumed that, at yield, the strength of the spray ice is insensitive to the magnitude of the normal stress acting on the failure plane, and the strength of aged spray ice is the same for both simple shear and triaxial loading. The data for simple shear and triaxial test presented by Chen and Gram (1989) substantiate this observation.

The results of a large number of triaxial strength test conducted by Imperial Oil give a good fit to a mathematical model of the form:

$$\tau = \log^{-1}(A - 1.65e + 0.18\log\dot{\epsilon} - 0.1T) \qquad (3.19)$$

where:

	τ	is the shear stress at failure
	e	is the void ratio as defined in Eq 3.6
	$\dot{\epsilon}$	is the strain rate (s^{-1})
	T	is the temperature (°C)
	A	is a material constant

The value of the constant A depends on the fabric and degree of saturation of the spray ice. The values of the constant A is given in Table 3.4 for dry and saturated spray ice. This value is given for both undisturbed and reworked spray ice.

Table 3.4 Value of A in Eq. 3.19

SPRAY ICE TYPE	DRY	SATURATED
Undisturbed	3.7	3.4
Reworked	3.5	3.2

3.4.3 Failure Model Comparison

It is of interest to compare the three failure criteria. Since the Mohr-Coulomb model requires a value of the overburden stress we will assume an island with a 6 m freeboard in water depth of 6 m. We will also assume that the density of the above-water spray ice is 600 kg m^{-3} and the buoyant density of the below-water spray ice is -100 kg m^{-3}. It is assumed that the driving force produces a strain rate of $1x10^{-4}$ s^{-1}. The spray ice temperature is taken to be -5 °C.

Using the Mohr-Coulomb model and data presented by Chen and Gram (1989) we find that the shear strength varies with depth. The minimum strength at the surface increases to a maximum at the water-line and then decreases below the surface. The Imperial model produces two values of shear strength; one value for the dry spray ice and a second value for the below-water spray ice. In calculating the strength using the Imperial model a value of A of 3.5 is used. Table 3.5 compares these values.

Considering Table 3.5. we see that the Imperial model gives one value of the shear strength of spray ice for the above-water ice and a second value for the below-water spray ice. In the Mohr-Coulomb model using the Chen and Gram data the minimum strength value is at the surface and increases with depth to the water line; the shear strength then decreases with depth below the water surface. This is a result of the value of σ (the overburden pressure) in Eq 3.11. The strength values derived from the Chen and Gram data are unrealistically low for the above-water spray ice. For the Karluk model the above water strength is constant and the below-water strength follows the same trend as described in the Chen and Gram data.

Table 3.5 Comparison of strength between the Imperial, Chen and Gram, and Karluk failure models

DEPTH BELOW SURFACE	SHEAR FAILURE STRESS (kPa)		
	Imperial	Mohr-Coulomb Chen and Gram	Karluk
0	160	11.5	146
6 (SEA LEVEL)	160/80	57	146/39
12	80	49	36

3.5 Thermal Properties

No specific investigations have been carried out on the thermal properties of spray ice, however, as with the mechanical properties the properties of snow can be used.

It should be noted the thermal properties are for dry spray ice. The data are taken from summaries of properties provided Mellor (1969a, 1977). The data on thermal properties is given in Table 3.6.

Table 3.6 Thermal properties of dry snow.

PROPERTY	VALUE	UNITS
Thermal Conductivity	1.5	w (m °K)$^{-1}$
Heat Capacity	2.0	kJ/(kg °K)
Specific Heat*	20.3	kJ/(kg °K)
Coefficient of Linear Expansion	5 x 10^{-5}	°C^{-1}
Latent Heat of Fusion	333.6	kJ kg^{-1}
Latent Heat of Sublimation @ 0 °C	2.834	MJ kg^{-1}

* Estimated or interpreted value

3.6. Summary

1. Spray ice is a bonded granular material similar to high density snow. Spray ice derives its strength from the growth of grain bonds formed during the sintering process. The strengthening of spray ice with time is referred to as sintering or curing.

2. Density is an important property in defining the strength of spray ice. Densities of above water spray ice are usually near 600 kg m^{-3}. The buoyant density of spray ice is typically in the vicinity of -100 kg m^{-3}.

3. In offshore spray ice operations island settlement will usually be the governing material property. Creep rates for from a number of spray ice structures are very similar. Overall creep strain rates observed have ranged from 2x10^{-9} s^{-1} to 8.5 x 10^{-9} s^{-1}.

4. Failure models based on the Mohr-Coulomb failure criterion are not realistic for above-water spray ice. This model may have more application for below-water spray ice.

4.0 DESIGN ANALYSIS

The primary design criterion force that must be considered in the design of spray ice islands is the force of the moving ice sheet against the spray ice island. The potential ice forces generated against a spray ice island will be primarily a function of the of the islands location. To calculate an exact ice force against a spray ice island the primary factors to be considered are the thickness, temperature and the anticipated velocity of the ice.

The minimum work area required for a spray ice island used as a drilling pad is determined by operational requirements. However, the actual area (or more correctly the volume) of the island will be determined by the mass of ice required to withstand the calculated ice forces.

Weaver and Gregor (1988) have discussed the analysis involved in the design of Angasak Spray Ice Exploration Pad. A similar analysis was used in the design of Nipterk Island (Imperial Oil Ltd. 1988).

In designing an ice island to withstand the potential ice forces three failure modes are considered. These modes are edge passive failures, spray ice simple shear failure and seabed failure. Figure 4.1. depicts these type of failures.

4.1 Edge Passive Failure

Failure mode (A) in Figure 4.1 depicts an edge passive failure. In this mode ice moving normal to the island fails the island's edge in shear. Using limiting equilibrium theory for a cohesive soil the edge resistance per unit width can be written as:

$$R_a = (\gamma H^2)/2 + 2\tau H \qquad (4.1)$$

where:

- R_a is the resistance (N m^{-1})
- H is the height of the island above sea level (m)
- τ is the shear strength of spray ice (Pa)
- γ is the weight density of the above water spray ice (N m^{-3}). γ is defined as,

$$\gamma = \rho g \qquad (4.2)$$

where:

- ρ is mass density of spray ice (kg m^{-3})
- g is acceleration due to gravity (9.8 m s^{-2})

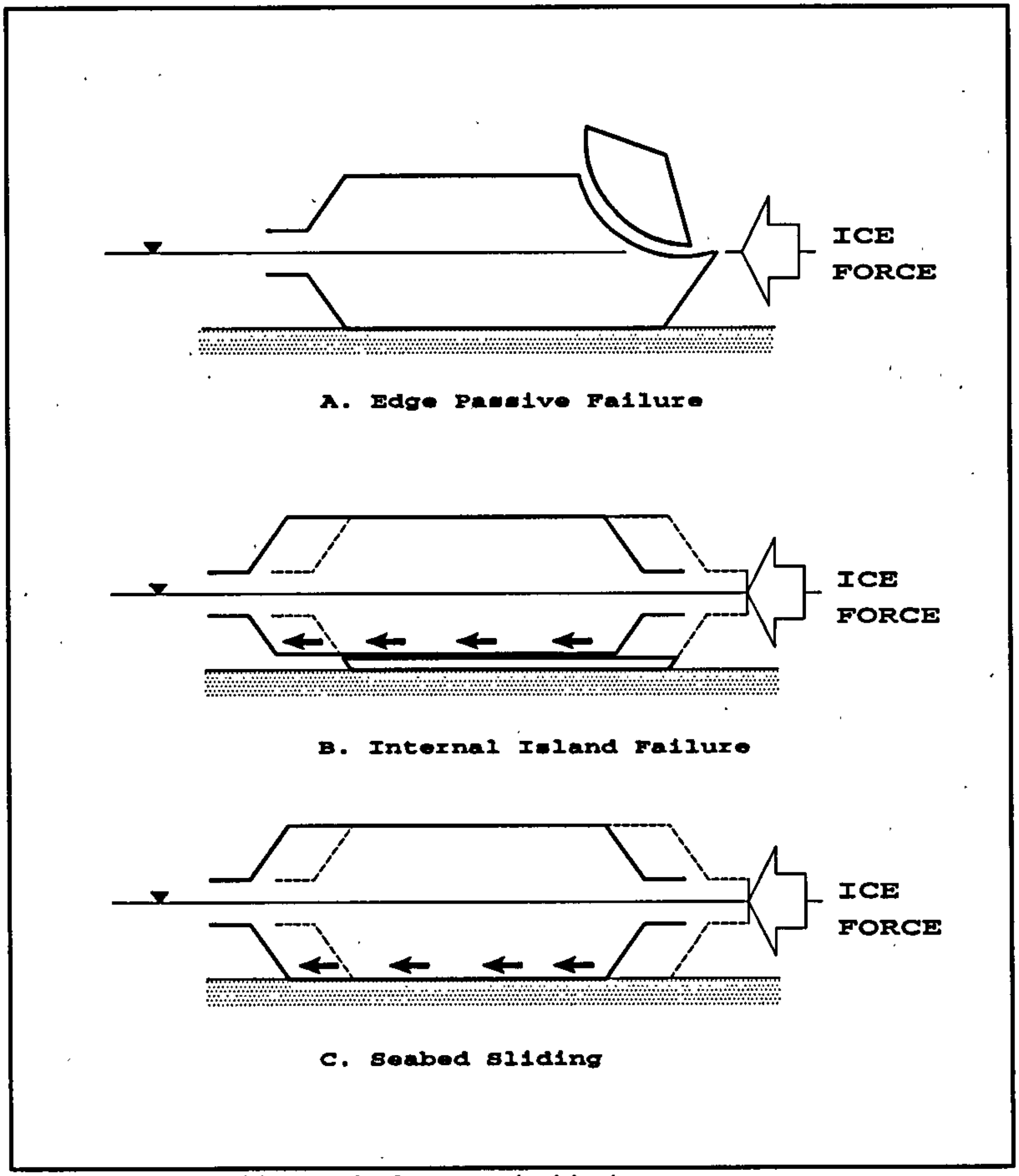


Figure 4.1 Potential failure modes for a spray ice island.

The design ice force is determined by the ice load and the safety factor to be employed in the design. The design ice load is:

$$R_d = F_1 I \qquad (4.3)$$

where:
- R_d is the design ice load (N m^{-1})
- F_1 is the safety factor
- I is the ice load in (N m^{-1})

Eq 4.1 assumes that the edge failure takes place in the above-water spray ice. As presented here the edge resistance is a function of the island freeboard and is independent of the diameter.

4.2 Internal Island Failure

Figure 4.1. depicts spray ice failure mode 'B'. For this type of failure a horizontal shear plane develops in the spray ice. The most likely location for this failure plane would be at the interface of the submerged spray ice and the grounded natural ice sheet. This region is the point of minimum overburden stress. Cone penetrometer test indicate that a qualitatively soft layer of spray ice often exists at this level. This soft layer can be discerned in the cone penetrometer log presented in the paper by Chen and Gram (1989).

The failure stress for internal spray ice failure can be obtained directly for the failure criteria developed in the last chapter. For internal spray ice failure, the failure load per unit width is given by:

$$R_b = D\tau \qquad (4.4)$$

where:
- R_b is the force per unit width for in plane failure (N)
- D is the diameter of the island (m)
- τ is the failure strength of the spray ice as determined from Eq 3.11 Eq. 3.19.

In-plane failure of the spray ice is a function of the island diameter only, using the Imperial failure model (Eq. 3.19). If the Mohr-Coulomb model is used in-plane failure of the spray ice is a function of the diameter and the effective overburden pressure through Eq. 3.11.

4.3 Seabed Sliding

The third failure mode depicted in Figure 4.1 is that of sliding of the island over the seabed. In this mode the failure takes place in the seabed material at the interface of the submerged natural sea ice and the sea floor. The model used for this type of failure is the same as employed for determining the sliding resistance of a gravel island. Modifying the analysis of Croasdale (1980) the resistance to sliding for a unit width of spray ice island can be written.

$$R_s = \alpha(\gamma H + \gamma' d) D \tan(\phi) \qquad (4.5)$$

where:

R_s	is the resistance to sliding per unit width (N)	
γ	is the weight density of dry spray ice (kN m^{-3})	
γ'	is the buoyant weight density of spray ice (kN m^{-3})	
h	is the island freeboard (m)	
d	is the depth of spray ice below water (m)	
D	is the grounded diameter of the island (m)	
ϕ	is the friction angle of the underlying material	
α	is the contact factor	

The contact factor α, which is less or equal to one, reflects the degree of contact that the underside of the island makes with the sea bed. If 85% of the island is grounded then the contact factor will be 0.85.

The seabed-island interface strength is dependent on the seabed shear strength near the mudline and the underside geometry of the island. For seabeds consisting of free-draining soils such as sand, the available interface shear strength is about 0.5 times the average vertical effective pressure. However, for very soft clays that persist over much of the Canadian Beaufort Sea Shelf the strength of this clay is often less than 3 kPa at mudline.

A number of potential methods are available to increase the interface shear strength between the island and the seabed (Weaver et al. 1991). These include:

- consolidate the weak soil
- penetrate the weak soil with broken ice at the base of the island
- remove the weak soil
- penetrate the weak soil with piles
- freeze the week soil

4.4 Safety Factor

Eq. 4.3 makes reference to a safety factor (F_1) to be used for the design ice load. Weaver and Gregor (1988) provide an equation for determining the safety factor related to sliding of the island on the sea bed. Weaver et al. (1991) provide further rationale for developing a safety factor against seabed sliding. Typically a safety factor of 1.5 is used when determining design ice loads for spray ice islands. This value is in line with customary safety factors values used in foundation design (Bowles 1982). A higher safety factor may be justified if the island has numerous vertical fissures. The higher safety factor is required to maintain low horizontal deflections at the well location during design ice load events.

4.5 Example Calculation

Considering the above equations we can look at their values they produces in terms of a hypothetical island design. For an example we consider a spray ice island in 6 m of water for which the ice load is determined to be 1.5 MN m^{-1}. From Eq. 4.3 the design ice load is 2.25 MN/m. We assume that the final above-water spray ice density is 600 kg m^{-3} and the buoyant density of spray ice is -100 kg m^{-3}. For yield stress of the above-water spray ice we will use a value 160 kPa. We will assume that the sea bed in the vicinity of the island is composed of dense silt with a friction angle of 25°. For spray ice strength values we use the Imperial Oil Strength Model and the data presented in Table 3.5.

The freeboard of the island will be determined by Eq. 4.1 which is used to determine the edge failure load while the diameter of the island is determined from either Eq 4.5 or 4.6 which describe the resistance to internal island failure, or seabed failure. In most instances the limiting failure mode will be as a result of island movement over the seabed.

Solving Eq 4.1 using the above values indicates that the freeboard of the spray ice should be 6.7 m. This gives an edge resistance of 2.27 MPa which is greater than the design load value of 2.25 MPa.

In nearly all instances the controlling factor in island design will be the sliding resistance of the island as determined from Eq 4.6. For the conditions stated the island design diameter is determined to be 170 m. This diameter indicates a sliding resistance of 2.27 MPa, again this value is greater than the calculated design load.

The development of an internal failure plain within the island is generally not a limiting criterion. Applying Eq. 4.1 we find that the force per unit width required to develop an internal shear plane is 13.6 MPa.

In terms of island design, once the island is constructed it is necessary to determine that the design parameters such as freeboard and spray ice density are consistent with the initial design requirements. If they are not, remedial measures must be taken. It should be noted that the design equation presented and the values used are representative of what might actually be used. There are other methods of calculation that are as equally effective.

4.6 Summary

1. In the design of spray ice islands ice forces will be the limiting design factor.

2. Ice loads must be determined individually for each island location considered.

3. In spray ice island design three potential failure modes must be considered: passive edge failure; internal island failure; and seabed failure that allows sliding or slippage of the island over the sea bed.

4. Island freeboard will be determined primarily by the requirement to protect against edge passive failures while the diameter of the island will be governed primarily by sliding of the island over the seabed.

5. In the example used a relatively strong seabed soil was employed. However, particular attention must be paid in determining seabed strength, using geotechnical surveys, since extremely weak soils exist in much of the near-shore Beaufort Sea.

5.0 CONSTRUCTION SCHEDULING AND EFFICIENCY

5.1 Construction Planning Factors

Construction scheduling is an important aspect of spray ice island design and in some instances may be the limiting factor determining whether a spray ice island will be feasible for drilling. The most important limiting factors are whether the spray ice island can be constructed, the well drilled and tested and the equipment demobilized within the winter time frame. In some if not all instances in addition to considering the drilling of the primary well(s) time must also be allowed for in the event a event that a relief well is also be required. A careful investigation of climatic and meteorological conditions at the intended site is required to evaluate the whether a spray ice island is appropriate.

In constructing a spray ice island a stable ice cover is required. Typically equipment will be mobilized over the ice, requiring the construction of an ice road. In the American and Canadian Beaufort Sea, ice road construction can not begin until sometime in November. Once the ice road is established it may take two months to complete the spray ice island and move a camp and equipment on to it. This gives an island completion date of late January or early February. Considering a 60-day drilling program, cessation of drilling activities and removal of equipment will take place in April. In any event, under normal circumstances the end of drilling operations must take place while ice roads are still usable. Under extreme circumstances it may be possible to demobilize equipment in late season or under open water conditions in order significantly increase the time available for construction or extending the drilling season (Weaver et al. 1991, Poplin et al. 1991).

In terms of the four spray ice islands and the spray ice barriers built in the American and Canadian Beaufort (Mars, Angasak, Karluk and Nipterk, Antares, Nome, & Red Dog) the earliest construction was started 22 October and the latest completion took place on 23 February. The shortest length of time to construct an island was 38 days, and the longest time was 60 days.

To give an idea of the efficiency of spray ice construction we define the term conversion efficiency which is the ratio of the volume of spray ice placed to the total volume of water pumped.
This value is cited without considering other factors such as temperature or site location. Table 5.1 summarizes these data.

Table 5.1 Construction times and efficiency

SITE	START DATE	END DATE	ELAPSE TIME (days)	VOLUME (m^3)	CONVERSION EFFICIENCY (%)
Antares	22 Oct	21 Dec	60	2,322,000	60
Angasak	7 Dec	3 Feb	58	356,000	89
Mars	8 Jan	23 Feb	45	771,634	45
Nipterk	28 Nov	20 Jan	53	825,000	105
Karluk	13 Dec	20 Jan	38	356,000	90

The average conversion efficiency for the Antares, Angasak, Mars and Karluk spray ice structures was 71%, i.e. for every cubic meter of spray ice placed in the island 1.4 cubic meters of water was sprayed. For Nipterk Island the conversion efficiency was 105%. The high production efficiency for Nipterk was a result of the island being constructed from fresh water. The primary factors affecting spray ice conversion efficiency are the amount of water that is converted into ice and that fraction of the spray ice generated that is placed in the target zone. As discussed in an Section 2.1, the amount of water that is converted into ice decreases dramatically for temperatures above -20°C. Similarly the amount of spray ice that is placed on site is reduced when the wind exceeds 8 m s^{-1} (15 kts).

The efficiency of converting water to ice is primarily related to meteorological factors and to the salinity of the water pumped. However, the length of time it takes to construct a spray ice island may depend on a number of other factors. Examining the elapse time in 5.1 we find that the average construction time for a spray ice structure is 51 days. For planning purposes it is important to consider why the construction time given in 5.1 appears to be independent of design volume.

The primary factors that delay spray ice production are weather, in the form of mild temperatures and storms and the time required for the spray ice to cure. Secondary factors are the time needed for equipment relocation, and maintenance and repair of equipment. A detailed breakdown of the various time variables associated with spray ice construction are available in the reports from Amoco (1986) and Bugno et al. (1990). A detailed account of the percentage of time spent on various functions for Mars Island and Karluk Island is presented in Figure 5.1.

From Figure 5.1 we can see that the major factor delaying construction for Mars island was waiting for the spray ice to cure (39.2%) while weather caused delays 13% of the. For Karluk Island weather delays represented 52.2% of the lost time and 18.3% of the time was used for curing. This is consistent with the construction of other spray ice structures. At Mars Island

7.7% of the time was spent moving and setting up equipment while 8.8% of the time was lost to mechanical requirements. At Karluk Island, 6% of the time was spent on pump moves and 5% of the time was spent on repair and maintenance.

At Mars Island the fraction of time spent actually producing spray ice was 22.5% and at Karluk Island the fraction of time spent on spray ice production was 18.8%. In view of earlier arguments it appears that curing time could be greatly reduced or rescheduled. With the curing time reduced the other would increase proportionately.

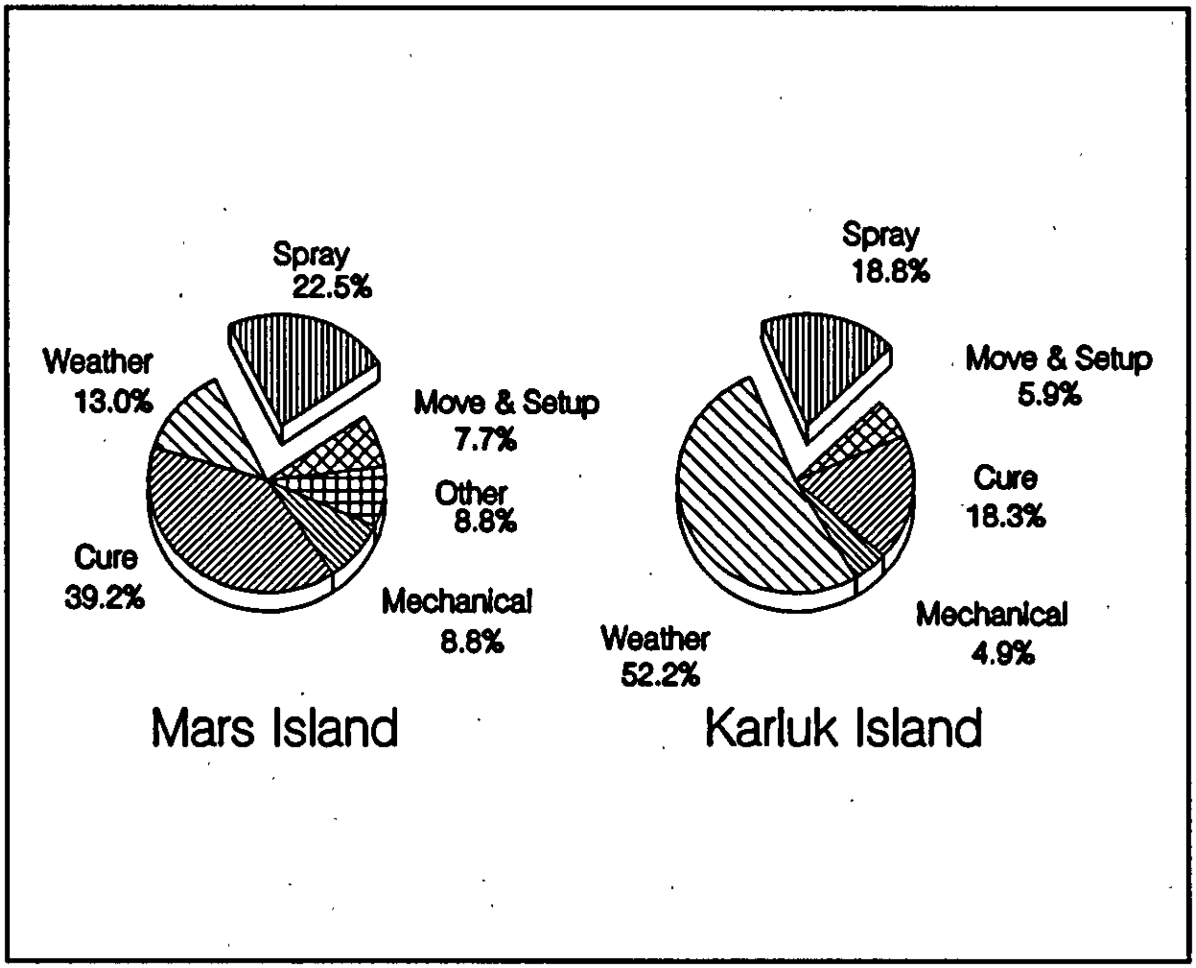


Figure 5.1 Spray ice production efficiency for Mars and Karluk Islands.

5.2 Summary

1. In planning a spray ice structure consideration should be given to the time it takes to mobilize the equipment, construct the island, perform the assigned task and demobilize the equipment. In general, equipment will be demobilized in the same manner in which it was mobilized.

2. On average, seawater will be converted to spray ice on a volume basis of 1.4 m^3 of water producing 1 m^3 of spray ice.

3. Pump capacity should be sufficient to produce the required volume of spray ice in approximately 25% of the time allotted for the construction period.

4. Construction of spray ice structures with fresh water may greatly enhance production efficiency.

5. Currently a large percentage of construction time is allotted to the curing process. Considering the structure of spray ice and the nature of grain bond formation, this time could be greatly reduced.

6. Sufficient lead time must be allowed for the permitting with regulatory agencies. In most instances the time require for permitting will exceed the time required to build an island and carry out drilling operations.

6.0 SPRAY ICE EQUIPMENT

The minimum equipment required to produce spray ice is relatively simple, consisting of a pump and a water monitor. The specifics may are more involved when capacity requirements and the operating environment are considered.

The two basic categories of spray ice systems are off-ice and land- based mobile units. For our purposes we consider off-ice systems as those that are constructed on a relatively permanent structure. For example, Global Marine Company's Concrete Island Drilling Structure (CIDS) or the spray ice system that was temporarily installed on Canmar's ice breaker the Kigoriak (Jahns et al. 1986) are considered fixed spray ice systems. Mobile units are skid-mounted pump and monitors that have been used to build the spray ice exploratory drilling pads.

A number of different pumps have been used in spray ice operations. The basic pump requirement is sufficient volume to deliver the quantity of water required within the time limitations of the defined construction period. In general the pump should be able to generate pressures from 1,200 kPa to 1,400 kPa, or in more standard pump terminology, be capable of producing a head of approximately 120 m to 140 m.

The water monitor and nozzles used in spray ice production are typically those used in fire fighting operations. The pressure and volume capacity of the monitor and nozzle should match the capacity of the pump selected.

6.1 Spray Ice Pumps

A number of different types of pumps have been used in spray ice operations. These have ranged from fairly high (60 m^3 min^{-1}) to moderate capacity pumps (3 m^3 min^{-1}) mounted on both off-ice and mobile delivery systems.

In terms of off-ice systems, a good deal of information was gained using a large pumping unit at the Mckinley Bay spray ice test mound, and the spray ice barrier at the Antares drill site (Jahns et al. 1986). During the Kigoriak trials in 1984 a containerized Thune Eureka water monitor with a capacity of 60 m^3 min^{-1}, driven by a 1,600 kW electric drive was used for constructing the spray ice test mounds at Mckinley Bay. The pumping system used on the Kigoriak had an operating pressure of 1,310 kPa. This unit had a water throw height of 76 m and a horizontal reach of 150 m.

At the CIDS Exxon Antares site the spray ice barrier was constructed using a pumping system with an 83 m^3 min^{-1} capacity which operated at a discharge pressure of 1,172 kPa. On the CIDS the pumping unit was connected to three water monitors with output capacities of 40 m^3 min^{-1}. The throw height of the CIDS system was 58 m above the nozzles. The water monitors were located approximately 15 m above sea level.

As seen in Table 5.1, the volume of spray ice produced was significantly more at the CIDS Antares site than at the four spray ice islands. In constructing the spray ice drilling islands, mobile pump units of significantly smaller pump capacity were used..

Masterson et al. (1987) report on the construction of the Cape Allison C-47 spray ice pad in the Canadian High Arctic using four 37 kW electric submersible pumps which had a volume output of 1.5 m^3 min^{-1}. The four pump units were powered by two 125 kW generators.

For the construction of the Angasak Spray Ice Island (Weaver and Gregor 1988) two single-stage, diesel-powered centrifugal pumps with a capacity of 8 m^3 min^{-1} were used. These two pumps were modified marine firefighting units mounted on skids. In addition, two skid mounted single-stage, diesel-powered centrifugal pumps with an output of 11 m^3 min^{-1} were also employed.

For the construction of Nipterk, four skid mounted similar to those used on Angasak were employed. Each of the four Nipterk pump units had an output capacity of approximately 11 m^3 min^{-1} at an output pressure of 1,500 kPa.

For the construction of Mars and Karluk Islands pumps larger than those used on Angasak and Nipterk were employed. At Mars and Karluk Island four 19 m^3 min^{-1} pumps capable of producing a head of 156 m (1,530 kPa) were used. On Mars Island the pumps were vertical turbine pumps, each powered by a 600 kW (800 hp) diesel engine. The horizontal throw distance for these units was 150 m.

For constructing Karluk Island two of the Mars Island pump units were modified by replacing the vertical turbine pumps with centrifugal pumps which resulted in a considerable weight saving.

Figure 6.1. is a graph showing expected spray ice production versus temperature for a 60 m^3 min^{-1} output and for a pump with 10 m^3 min^{-1}output. This figure is adapted from Amoco et al. 1991.

6.2 Spray Ice Monitors and Nozzles

The spray ice monitor acts to direct the water from the pump to the nozzle. Typically the water monitors used for spray ice operations are either standard land based or modified marine monitors used in firefighting operations. The water monitors are available from a number of commercial vendors.

The water monitor needs to be sized to the pump used. The monitor must have the capability of being rotated over a wide angle in the horizontal plane and also have vertical angular control over the nozzle.

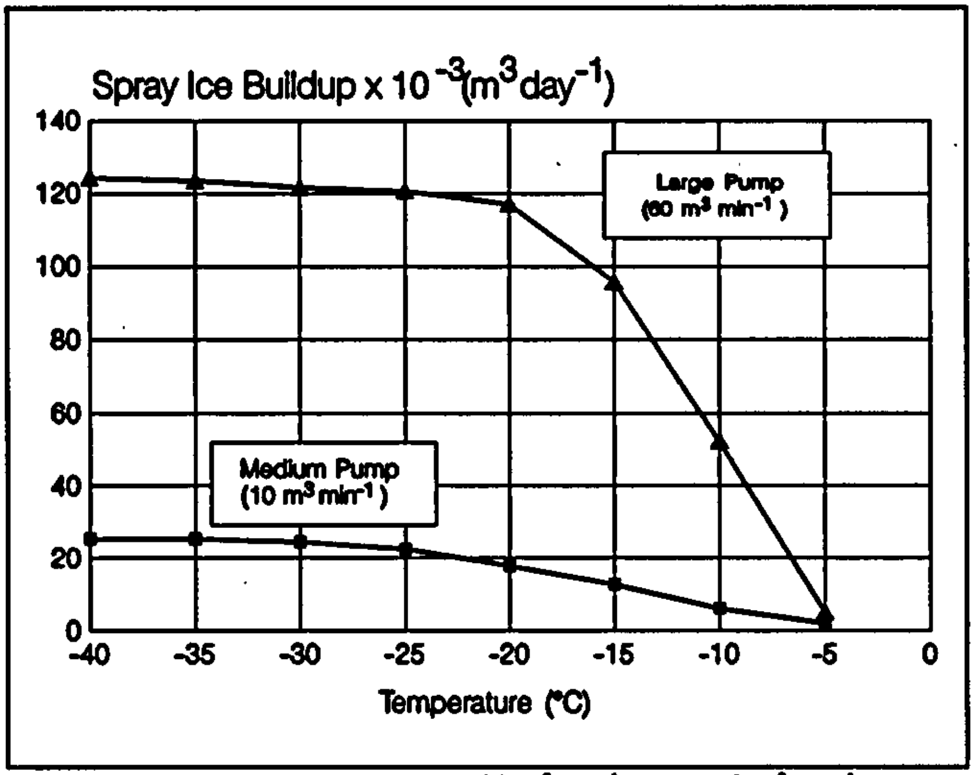


Figure 6.1 Spray ice production for a 60 m^3 min^{-1}, and a 10 m^3 min^{-1} pump as a function of temperature.

In the most basic form the water monitor can be manually controlled in both the azimuthal and vertical planes. For monitors with high volume outputs, manual control may not be practical and mechanically or hydraulically activated monitors will be required. Monitors with an auto sweep function were used in the construction of the Angasak Spray Ice Island.

Like the water monitor the nozzle used for spray ice production is primarily a commercially available standard fire nozzle.To some extent the nozzle used will be dictated by what is available for the monitor employed. Some experimentation with nozzles has determined that solid cone (straight stream) nozzles produce good results.

Allyn and Masterson (1989) report that the hollow cone adjustable nozzle which can be adjusted from a straight stream to a fog nozzle has been used effectively. The problem with this nozzle is that its reach in the fog or partial fog configuration is limited. They also report that a solid cone nozzle with a stream breaker is very effective in producing spray ice. In this configuration the higher pressure drop across the nozzle which produces a finer droplet. Their complaint about spray ice produced with this nozzle was that the ice crystal content was too high.

This complaint may not be justified when we consider that the submerged spray ice will rapidly metamorphose into an equilibrium structure and the above water spray ice at a somewhat slower rate. However, with an initially lower free water content the density of the dry spray ice will be lower and the sintering process may be somewhat extended.

To optimize spray ice production a range of nozzle sizes and configurations must be available to effectively accomodate for changes in temperature and wind conditions.

6.3 Spray Ice System (mobile)

We have considered separately the components of the spray ice system: the pump, monitor and nozzle. For off-ice spray systems the configuration of the components is not as critical as for land-based mobile units. In designing a mobile system a primary concern is to keep the unit light enough to be easily moved from place to place during construction, and to provide a design that will operate efficiently in the winter arctic environment.

Each of the spray ice units used for the construction of the Mars Island was quite large: The total mass of each was 37 tonnes. With this mass an ice thickness of 1.2 m is required to move the units safely over the ice, precluding early mobilization.

Much of the weight of the Mars units is attributed to the vertical turbine pumps used and the auxiliary equipment required for their operation. The Mars units were somewhat difficult to move from place to place, and to position over the pre-drilled water intake holes. For the construction of Karluk Island, which used the Mars Island spray systems, the vertical turbine pumps on two of the units were replaced with horizontal centrifugal pumps. This reduced the weight of the units to 19.5 tonnes. Reducing the weight of the pump units reduced the ice thickness requirement for operation was to about 80 cm.

The spray ice systems used to build Angasak and Nipterk were considerably more compact than those used on either Mars or Karluk. The pump output was also 50% of the Mars and Karluk units. These smaller units allowed ice spray operations to be carried out earlier in the Canadian Beaufort Sea than in the American Beaufort.

In designing a spray ice production unit consideration should be given to mobility and ease of operations in the arctic environment. The pump and auxiliary equipment should be enclosed. An auxiliary generator should be included to provide power for both interior and exterior lighting and heat when the pump is not operating. The layout of the unit should provide for easy maintenance and repair.

The monitor mounting may be designed as an integral part of the pumping unit or as separate unit attached to it. All external plumbing should be heat traced to prevent freeze-up of critical components.

6.4 Spray Ice System (off-ice)

Successful operations with off-ice equipment have been carried out in both the United States and Canada (Jahns et al. 1986) and the benefits and problems of using off ice production units are considered by Weaver et al. (1991). Off ice systems are generally more reliable than mobile units and maintenance and repairs that can be carried out in the relatively friendly environment within the platform from which these units operate.

The primary benefits of the off ice production system are:

- Large capacity pumps can be used since weight restrictions imposed by ice thickness limitations are not a factor.Thissignificantly increases the volume of spray ice that can begenerated (see Figure 6.1).

- If the off-ice production system can be placed on location inthe early season spraying can begin as soon as temperaturesdrop low enough (often in October) and an ice cover forms.This allows operations in deeper waters than would be be be practical with on ice-mobile systems.

Considering the rapid buildup rates using the CIDS and Kigoriak and the construction techniques it might be useful to consider spray ice structures built from ice breakers. The primary limitation for operating from ice breakers is that for shallow water sites (less than 6 to 10 m) ice breakers are draft limited. Weaver et al. 1991 suggest that spray ice islands may be feasible in water depths up to 16 m if spray is carried out from marine vessles or from a spray rubble generator platform.

6.5 Summary

1. For spray ice operations pumps capable of producing a head of120 m to 140 m are required. Pumps with capacities ranging from 10 m^3 min^{-1} to 60 m^3 min^{-1} have been used successfully from both off-ice and on-ice mobile spray ice units.

2. Water monitors and nozzles used in spray ice operations are standard units used in firefighting operations. The mosteffective nozzle and the one most often employed is the solid cone unit.

3. Design of mobile spray ice production units should pay particular attention to minimizing the weight forthe amount of water pumped. Also particular attention shouldbe paid to making the unit as efficient as possible in terms of operation and maintenance while considering the working environment. Attention should also be paid to keeping the center of gravity of the unit low and use a well engineered skid and sled arrangement.

4. In spray ice construction, consideration should be given to the cost effectiveness of using off-ice platforms such as ice breakers where water depth does not preclude their use.

7.0 DESIGN AND CONSTRUCTION METHODOLOGY

Several different design layouts have been employed for spray ice islands in an attempt to minimize construction time or to provide maximum protection from ice loading. For the spray ice barrier at the CIDS Antares site the primary goal was to provide a mass of spray ice sufficient to protect the structure. For the spray ice islands used as drilling platforms the spray ice structure not only has to offer protection from ice loads but also provide a work surface on which a drilling camp can be located and a well drilled.

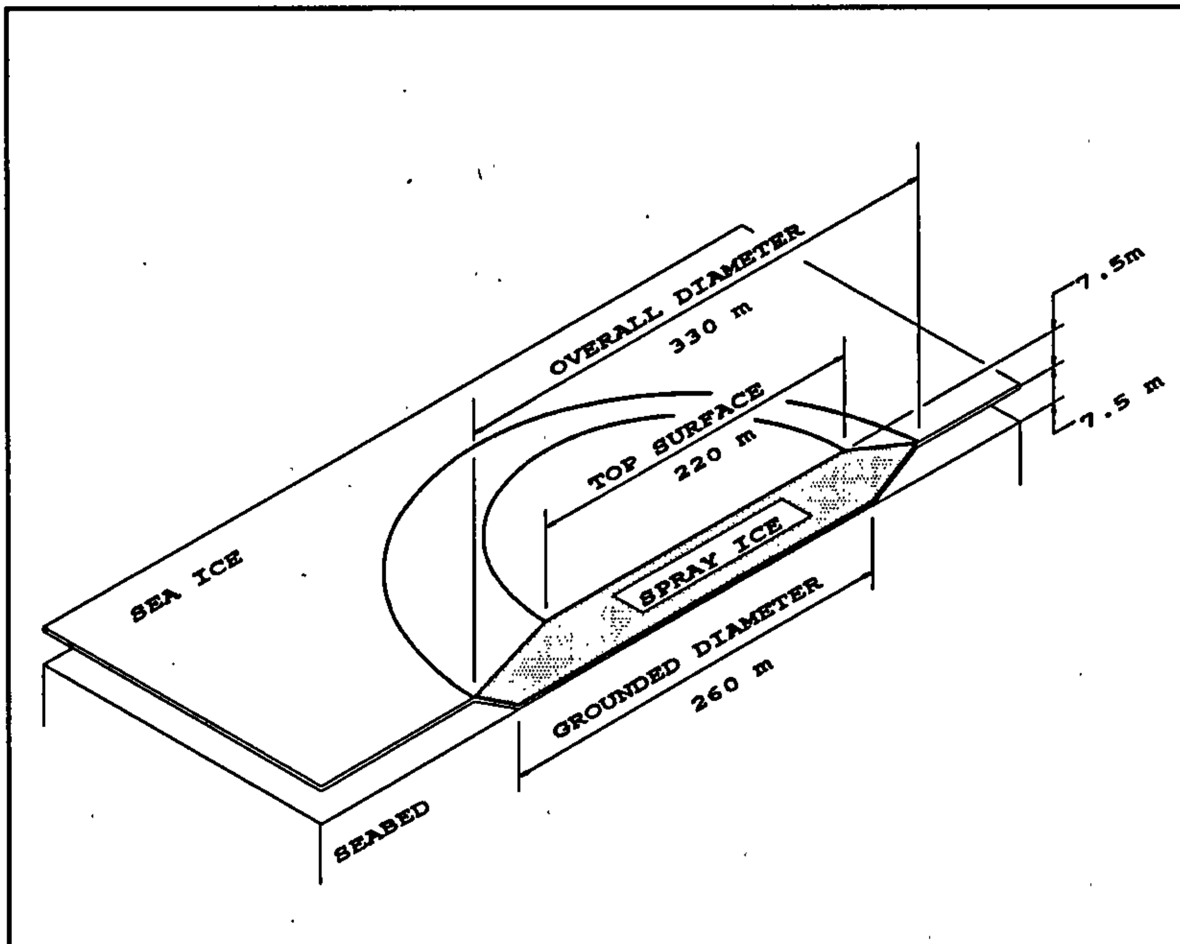


Figure 7.1 Isometric cross-section of a spray ice drilling island. Dimensions are based on the Mars Island as-built.

Figure 7.2 depicts an isometric cross-section of a spray ice island. The dimensions are based on the Mars Island design. The minimum diameter of the spray ice island is dictated by the required working surface for the operation being undertaken. The overall diameter, height and the freeboard will in most instances be dictated by ice load parameters. The typical spray ice drilling pad is circular, or nearly circular, with a grounded core and tapered edges. Access onto the island is usually provided by means of a low angle ramp.

7.1 Construction Techniques

A number of methods have been employed to construct spray ice structures. At the CIDS Antares and the CIDS Orion sites (Jahns et al. 1986, Chen and Gram 1989) the structures were built using continuous spraying as weather permitted. In this method no consideration is given for a cure time for the spray ice material. For the construction of Mars Island, Karluk Island and Angasak Island the structures were constructed in "lifts," with a period being allowed between each lift. As can be seen from Figure 5.1 at Mars Island 39 % of the total construction time was devoted to curing and at Karluk Island 18% of the total time was devoted to curing.

At the Nipterk site (Weaver et al 1991) the spray-and-cure approach was not used to any great extent and the island was brought to grade using much thicker lifts. At Nipterk pump moves were controlled predominantly by wind changes and requirements for controlling island geometry.

The spray ice barriers constructed at Nome and the spray ice jetty and barrier constructed at the Red Dog Port Site, south of Kivolina, Alaska, were constructed using continuous spray techniques and also by mining naturally deposited snow from adjacent areas. At these two sites a supplemental spray ice source was required since the temperatures were often above freezing during the construction period.

Comparison of the properties of the in-place spray ice at these sites indicates no significant difference in spray ice properties. Chen and Gram (1989) address the properties of continuously spray ice and conclude:

"Strength and deformation data indicate that spray ice deposited by continuous spraying has adequate foundation strength for spray ice drilling platforms."

The two primary reasons for building spray ice structures in layers or "lifts" is to let the material cure or gain strength, and to insure that the island grounds evenly to avoid cracks.

As Weaver et al. (1991) point out in the case of Nipterk, which was built on uneven and broken ice, it was impossible to avoid extensive cracking during construction. However, they found that the cracks generated by uneven grounding could be safely accommodated in the design and construction of the island. It should also be noted that surface cracks that appear during construction can be filled with spray ice producing a repair that leaves the disrupted region with a strength and appearance indistinguishable from the surrounding material.

Weaver et al. (1991), like Chen and Gram (1989), also found by considering cone penetrometer tests (CPT) and settlement records that the continuously sprayed ice rapidly metamorphosed into competent ice. This is to be expected in light of our previous discussions on the physical properties of spray ice.

It should also be noted that large-scale snow structures constructed in Antarctica and Greenland are made from dry mined snow. Again, through the process of sintering and metamorphism these structures in their final form exhibit strength properties comparable with what we come to associate with spray ice.

Possibly the concept of allowing the spray ice to cure in lifts came from the experience of attempting to operate equipment over newly sprayed ice. In the early stages of formation, spray ice is indeed a cohesionless mass. However, its final strength is derived from an aging process that takes place in the entire mass of spray ice and is not limited by whether the spray ice is produced in small or large quantities.

Construction of spray ice structures requires a certain amount of reworking and placement of material using earth-moving equipment. This has been minimal in spray ice islands to date since the circular nature of the islands lend itself to spray construction.

However, in linear structures such as the barrier at Nome or the jetty at the Red Dog Seaport, it is difficult to place the material strictly by spraying. In these instances extensive use of earth-moving equipment was required. Again, there appears to be no apparent difference in the mechanical properties of spray ice or snow that is manufactured in one location and transported or bulldozed a new location.

In terms of constructing spray ice drilling platforms it may in some instances be advantageous to keep the pumping and spraying equipment in a fixed location for the production of a stockpiled
volume. The material can then be moved to form the drilling platform using standard earth-moving techniques. It should be noted however, that a learning period is often required for heavy equipment operators when they first try to operate with spray ice. It has been our experience that operations on relatively young spray ice are greatly facilitated if earth moving equipment configured for low ground pressure (lgp) operations as used.

7.2 Aging and Surface Hardening

As previously indicated, spray ice hardens and to some extent its density increases with time. Typically there is sufficient time for aging of the spray ice during the construction and verification phase of the island. By the time the island verification program is completed the initial rapid settlement of the island should be in its final phases.

If left undisturbed the spray ice surfaces hardens naturally. In the case of Mars and Karluk Islands surface hardening was enhanced by treating the surface with fresh water. Fresh water was distributed on the surface using water tankers. The water percolated some distance into the spray ice and froze. Repeated application of water produced a very hard surface over which high ground pressure vehicles could operate without problems.

In the case of the spray ice jetty built at the Red Dog Port Site above freezing temperatures precluded the use of hardening the surface with water. In fact, melt water formed puddles on the spray ice surface. To counter the effects of surface melting, a 15 cm layer of gravel was spread on the spray ice surface. This produced a very hard surface and inhibited the ablation of the jetty work surface. At the end of operations the gravel layer was removed.

To a great extent the amount of surface hardening required, if any, will depend on the intensity and frequency of traffic on the island surface.

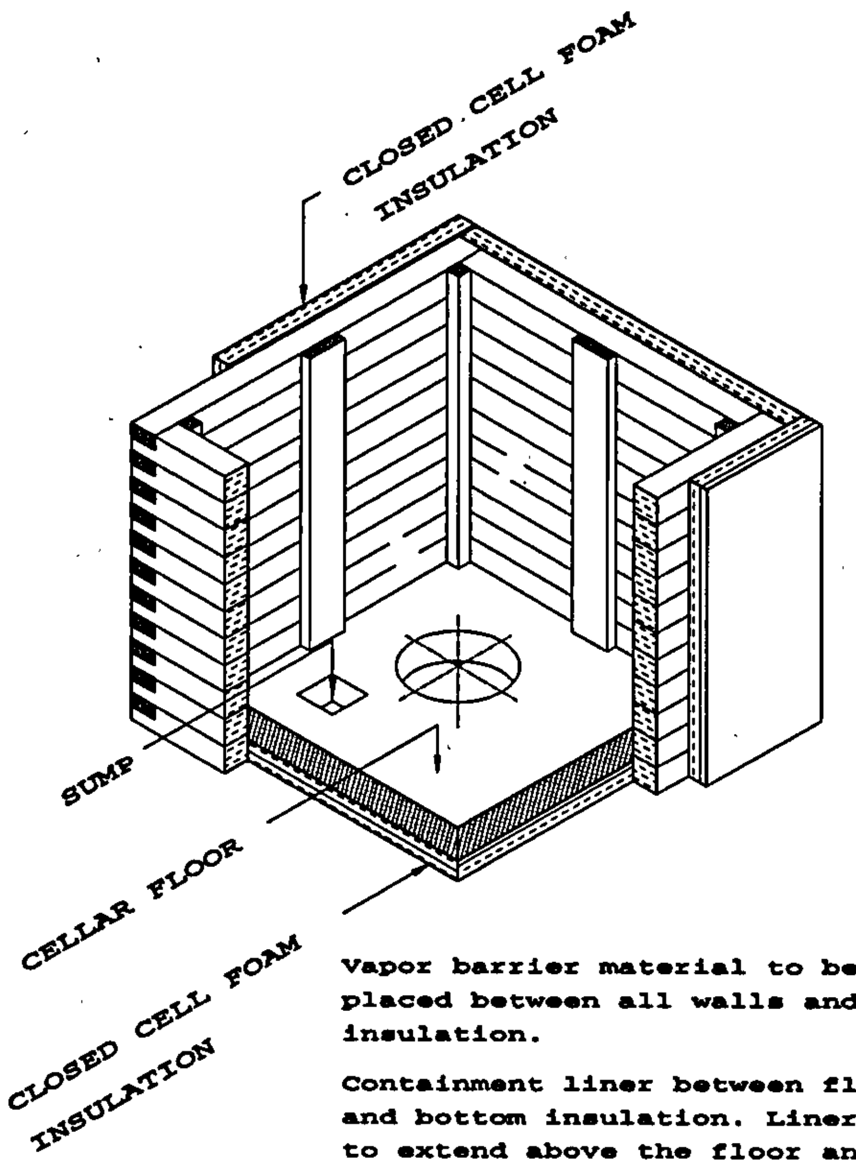
7.3 Placement and Design of the Well Cellar

The well cellar should be placed after the construction of the island work surface is complete. The well cellar area can be surcharged with spray ice and then removed prior to installation. In this way settlement of the spray ice after the cellar is installed can be minimized. If well cellar placement takes place concurrently with island construction, substantial settlement will take place due to the initial settlement and aging of the island. This is documented by Funegard et al. (1987) in the construction of the Mars Island.

After the island is completed an excavation should be made in the island for the well cellar. The well cellar should then be set, back filled, tamped and refrozen in place.

Figure 7.2 is a cutaway view of a typical well cellar that might be employed on a spray ice island. The emphasis in this design is on providing insulation between the spray ice and the interior of the well cellar. For this purpose a timber crib design might be used with a layer of closed cell foam around the exterior of the cellar itself. A vapor barrier membrane is placed between the timber and the insulation. The floor of the well cellar must be impermeable and provide a fluid tight seal between the conductor. Provisions are made for a sump so that drilling fluids accumulating in the cellar can be pumped out.

Particular attention must be paid to the well cellar during drilling operations since warm fluids draining through the cellar can seriously degrade and erode the spray ice in the area.



Vapor barrier material to be placed between all walls and insulation.

Containment liner between floor and bottom insulation. Liner is to extend above the floor and walls and be sealed at the conductor.

Figure 7.2 Typical prefabricated well cellar layout.

7.4 Conductor

The conductor, like the well cellar, comprises a region where thermal erosion of the spray ice can take place. Some concern was experienced on Mars Island due to the apparent formation of a thaw bulb around the conductor (Amoco 1986). At Mars Island the conductor was insulated but no active measures were employed to alleviate melting. It should also be noted that this apparent thawing had no noticeable at the surface.

At the Angasak, Karluk and Nipterk sites refrigerated conductors were used to eliminate this problem. The purpose of the refrigerated conductor is to remove heat generated by the wellbore during drilling before it can be conducted into the adjacent spray ice. Figure 7.3. presents a cutaway and schematic view of a for the design of a refrigerated conductor. For this design the working fluid is a calcium chloride brine which is environmentally benign.

The design is a closed system in which brine passes through a chilling unit and into the annulus formed by the conductor and the cooling jacket. The brine exits the injection tube near the mudline and is removed by the brine return tube at the top of the cooling jacket.

Some attention must be paid to sizing the chilling unit so that the brine is maintained at a temperature below the freezing point of the spray ice, but is high enough that it does not cause congelation of the drilling fluids.

At this time it is not known whether refrigerated conductors are an absolute necessity. This will not be established until more research is carried out on the thermal environment in the vicinity of the well bore. The problems encountered with refrigerated conductors are associated with the chilling system. Some consideration should be given to circulating cold seawater in the cooling jacket. Using cold seawater would minimize the complexity associated with pumping and eliminate the refrigeration unit. The remedial measure used at Mars island was to circulate seawater in the "moonpool" with apparently good results.

7.5 Summary

1. Spray ice structures can be made using spray-and-cure methods or continuous spray methods with little apparent effect on the quality of the spray ice.

2. Spray ice to some extent can be treated as other granular construction materials in that it can be produced in one area and transported to its final location using standard earth-moving and shaping techniques.

3. If there is an abundant supply of snow available it can be used as a substitute or in conjunction with spray ice. An important corollary to this is that in situ snow should not be removed prior to commencement of the spraying operation.

4. Spray ice surfaces may be hardened, if required, using fresh water or gravel. In some situations gravel may not be an acceptable environmental solution.

5. Well cellars or other structures to be placed in the spray ice should be placed after construction if their position is critical.

6. A Refrigerated conductor may be required to inhibit thermal degradation of the spray ice structure.

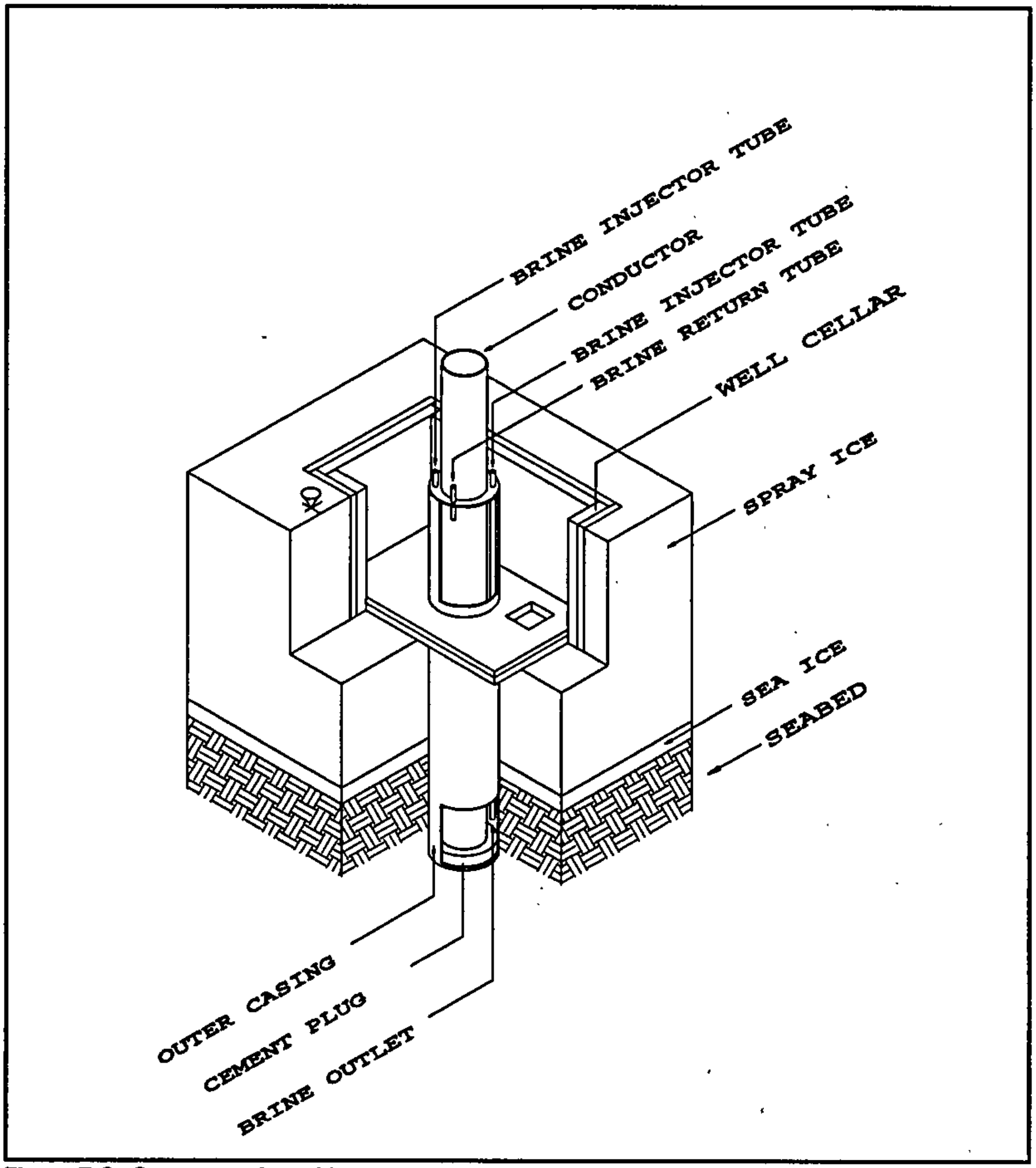


Figure 7.3 Cut away of a refrigerated conductor.

8.0 DESIGN VERIFICATION

Once the spray ice island is constructed, verification of the design must be performed. Typically the verification is a physical inspection of the spray ice structure that insures that the island as constructed meets the original design parameters and is generally required by the regulatory agency. If one or several of the design parameters are not met, then remedial measures are required. Typically the factors investigated in the design verification procedure are geometry, seabed strength, spray ice density, and ice sheet thickness and integrity.

8.1 Geometry and Structure

After the island is completed its as-built geometry must be assessed. This can be done using standard surveying methods to determine island elevations and overall size.

To determine the extent of grounding of the island a sufficient number of holes must be drilled to provide a statistically significant sample for calculating the degree of island grounding. Since the number of holes required may be in excess of 100 a hot-water drill is usually used. With experience the drill operator can determine whether voids are present as the drill probe penetrates the native ice sheet and into the sea bed. It should be noted that very little information regarding the integrity of the spray ice can be retrieved using a hot water drill.

To obtain statistically significant information on island grounding, 135 thermal drill holes were made at the Mars Island. Seventy thermal drill holes were drilled at Angasak Island and 125 thermal holes were drilled at Nipterk.

Cone penetrometer tests (CPT) are carried out to assess the structural integrity of the spray ice island.The CPT provides a qualitative view of the structural integrity of the island and can detect voids and areas of weakly bonded spray ice.

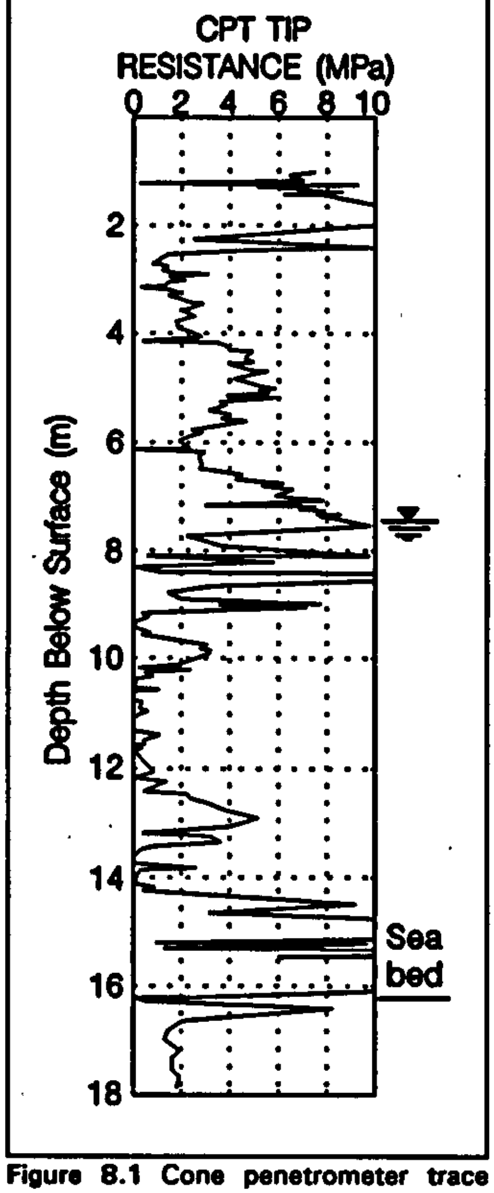


Figure 8.1 Cone penetrometer trace from Mars Island.

Particular attention to the spray ice structure must be given to regions of the island where high intensity loads are to be placed. Typically between 13 and 20 CPT are to be placed. Typically between 13 and 20 CPT profiles have been collected from each of the spray ice islands constructed to date.

Figure 8.1 shows the trace of cone penetrometer tip resistance graphs for Mars Island. This CPT tip resistance profile is typical for spray ice. On the profile a relatively weak layer can be detected just above the submerged native sea ice (at the 14 m depth mark). This feature is commonly detected in CPT logs of spray ice and may represent a very weakly bonded layer at the sea ice-spray ice interface.

For spray ice structures that must sustain relatively large loads and are used for environmentally sensitive operations such as drilling oil wells, cone penetrometer tests should be conducted prior to the beginning of operations.

8.2 Spray Ice Density

Once island construction is completed, spray ice density must be determined. This information, used in conjunction with geometry data, allows calculation of the stability of the island in regard to design ice loads. Design densities are likely to differ from actual in-place density. Table 8.1 presents the design densities and averaged measured densities for the four spray ice islands. In the cases where the actual density is less than the design density, mass will have to be added to the island.

Table 8.1 Comparison of design and measured densities.

Island	Design density (kg m^{-1})	Measured density (kg m^{-3})
Mars	640	663
Angasak	600	700
Karluk	641	620
Nipterk	600	550

Below-water densities are more difficult to measure because pore water escapes during core retrieval and there is uncertainty about the amount of entrained air. The overall buoyant density can be determined by measuring the freeboard height at the time of grounding or prior to grounding. The buoyant density can be calculated from on site observations from the equation:

$$\rho' = -\rho(h_1/h_2) \qquad (8.1)$$

where: ρ' is the buoyant density of spray ice (kg m^{-3})

ρ is the dry density of spray ice (kg m^{-3})
h_1 is the height of the spray ice above water (m)
h_2 is the depth of the submerged spray ice and natural ice (m)

For Mars Island the design value for the buoyant density was -80 kg m^{-3}; an in-place value was not determined. For Angasak Island the design value was -100 kg m^{-3} and the in-place value was calculated to be that. For Nipterk Island the buoyant density was determined to be -90 kg m^{-3}.

The density of the above-water spray ice is determined from cores retrieved from the island. As with determining the area of island grounding the sample size must be large enough to establish a statistically significant sample.

For Mars Island the above-water spray ice density was determined from 59 samples taken from 14 bore holes. At Nipterk continuous cores were taken from three bore holes.

8.3 Seabed Strength

Reliable information on seabed strength should be available from geotechnical surveys conducted prior to island construction. It is difficult to obtain measurements of seabed strength after the island is built are difficult to obtain due to to the disturbance that takes place during sample retrieval. Some information on seabed strength can be derived from in situ methods such as cone penetrometer, gravity penetrometer or shear vane tests.

8.4 Ice Thickness and Integrity

Ice thickness should be measured at the completion of construction and the values compared with those used to determine design ice loads. An evaluation of the ice sheet integrity in the vicinity of the island should also be made. In most instances a tidal crack will form near the perimeter of the spray ice island. This crack will open and close depending on ice movement direction.

8.5 Summary

1. To assure that the island meets the design standard a verification program must be undertaken.

2. As part of the verification program a survey is made to determine island geometry, to measure the extent of grounding and investigate the spray ice structure.

3. To be assured the island has sufficient ice load resistance measurements of both the submerged and above-water spray ice should be made.

9.0 PERFORMANCE MONITORING

Spray ice, unlike many construction materials, is used close to its melting point and as such can be drastically affected by changes in environmental conditions. Temperatures above the melting point or the loss of sea ice cover can have serious effects on a spray ice structure. For this reason a comprehensive monitoring program is required for spray ice structures on which environmentally sensitive operations are carried out or where loss of life or equipment could occur.

For the four spray ice drilling structures that have been built fairly extensive monitoring and alert programs have been implemented. At Mars, Angasak, and Nipterk Islands the following parameters were monitored:

- Natural ice movement.
- Magnitude and direction of ice pressure.
- Lateral deformation and movement of the spray ice.
- Spray ice settlement.
- Settlement of key structures.
- Spray ice temperatures.
- Meteorological data.

The degree of monitoring required will in part be determined by the location and potential for environmental changes that can adversely affect the structure. At Karluk Island sea ice movements and pressures were not measured.

In considering the monitoring of spray ice islands we have depended primarily on information supplied by Amoco Production Company and Imperial Oil Ltd. There is little in depth discussion of island monitoring in the open literature. Island monitoring at the Mars Angasak and Nipterk Island sites exceeded that specified by the regulating government agencies.

9.1 Sea Ice Movement

The standard instrument for measuring ice movement in the vicinity of spray ice islands is the wireline ice movement station (WIMS). These units are placed on the native ice sheet with one or more wires anchored to the seabed. As the ice moves wire is either fed out or taken in by the movement station. The movement of the wire is recorded and with signal processing can be used to record ice movements and/or alert operators of ice movement.

At the Nipterk site two WIMS were installed on the natural ice sheet approximately 500 m to the north and south of the island center. The data from the ice movement stations were telemetered to a data acquisition unit located on the island. Ice movement activity was sampled at 30-second intervals. Over the course of operations a maximum ice movement of 4.5 m was recorded. The maximum magnitude of hourly ice movement rates recorded at the south station was about 0.8 m s^{-1} and <0.2 m s^{-1} at the north station. In addition to the two WIMS, three tide crack gauges were placed at the tidal crack on the north, west and south-southeast side of the island.

At Mars Island five WIMS were employed. As with Nipterk the ice movement information was telemetered to a data acquisition unit located near the island. Over the operating life of Mars Island a total ice movement of just under one meter was recorded.

9.2 Ice Forces Measurements

Ice forces were measured at both Mars Island and Nipterk Island. At Mars Island three locations approximately 60 m from the perimeter of the island were selected for ice load measurements . These units were located in the northeast, northwest and southeast sectors of the island. At Mars Island two different types of load measuring devices were employed at each site.

At Nipterk Island twelve full thickness Exxon ice pressure panels were installed symmetrically around the island at a distance of 240 m from the island center.

For both the Mars and Nipterk sites data were telemetered to the data acquisition unit on or near the island.

9.3 Lateral Deformation and Movement of the Spray Ice

Lateral deformation of spray ice islands can be measured with slope indicators and in-place inclinometers and can be supplemented with trigonometric surveys.

At Mars Island 10 slope indicator sites were established and were read manually. Three of the slope indicator sites were configured with in-place inclinometers, each with five sensors installed from below sea level and through the island. The output of each sensor was telemetered to the data acquisition unit. Lateral movements during the measurement period were small, ranging from 11 mm to 74 mm..

At Nipterk Island five slope indicators and three in-place inclinometers with six sensors each were deployed. The slope indicators were read manually once a week and the in-place inclinometers were tied to the data acquisition system and sampled at 30-second intervals. In addition a trigonometric survey of the island surface using the slope indicator tubes as benchmarks was made on a monthly basis. During the early stages of monitoring island displacements of 12.5 mm were recorded and a relative island displacement of 19 mm was measured during a thermal ice loading event. Figure 9.1 is shows the lateral displacement measured from a slope indicator located at the southwest of Nipterk Island. The initial, vertical slope indicator bore-hole was set on 13 January 1989.

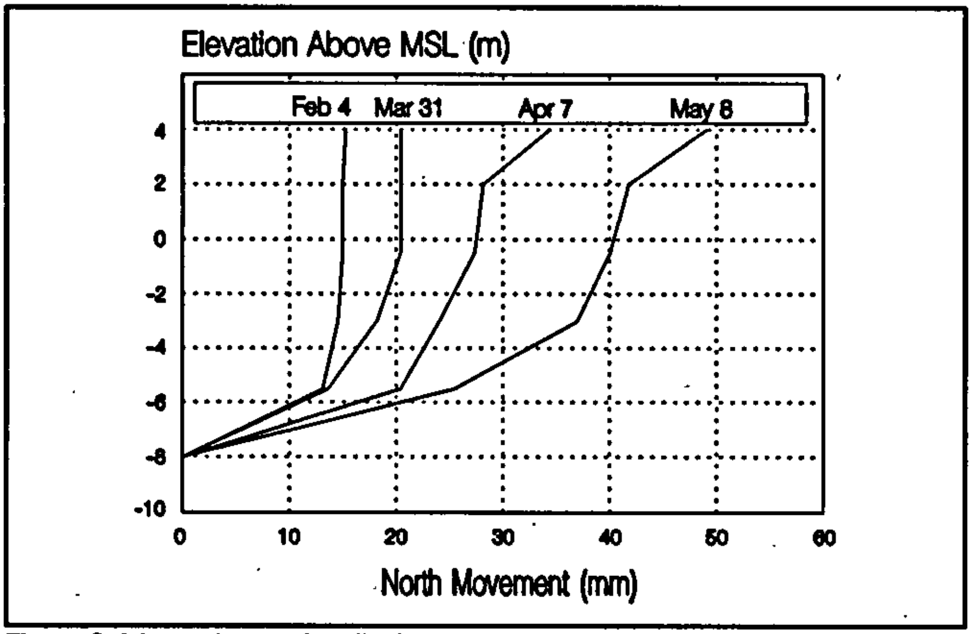


Figure 9.1 Lateral spray ice displacement at Nipterk Island from slope indicator measurements (Imperial Oil Ltd. 1991).

9.4 Spray Ice Settlement

Spray ice settlement at Mars Island was measured with seven Sondex settlement tubes and five settlement rod arrays. The readings from both the Sondex settlement system and the settlement rods are made manually. At Mars Island total settlement for the period from island completion (25 February 1986) through demobilization (25 April 1986) ranged from 0.265 m to 0.411 m.

At Nipterk Island five Sondex settlement units were installed and read manually once a week. At Nipterk the total settlement from 12 January through 18 May 1989 ranged from 0.195 m to 0.355 m. Figure 9.2 shows the spray ice settlement for one of the Sondex settlement units. The initial reading at this location was made on 14 January 1989. The magnitude of this data is consistent with total settlements recorded at Mars Island and Karluk Island (Amoco 1986, Bugno 1990).

9.5 Settlement of Key Structures

At Mars Island total settlement and differential settlement of the rig substructure was measured by level survey of the four rig corners, utilizing a built-in settlement rod as a reference bench mark. Total settlement of the rig substructure corners from 16 March to 18 April 1989 ranged from 158 mm to 174 mm for a maximum differential settlement of 16 mm.

At Nipterk settlement of the drilling rig was also conducted by level survey. Technical problems with the level instrument did not allow accurate measurements before 1 April. For the first three weeks of April it was found that differential settlement of the rig was less than 35 mm. It was also noted that there was no evidence to suggest that there was more settlement in the vicinity of the rig.

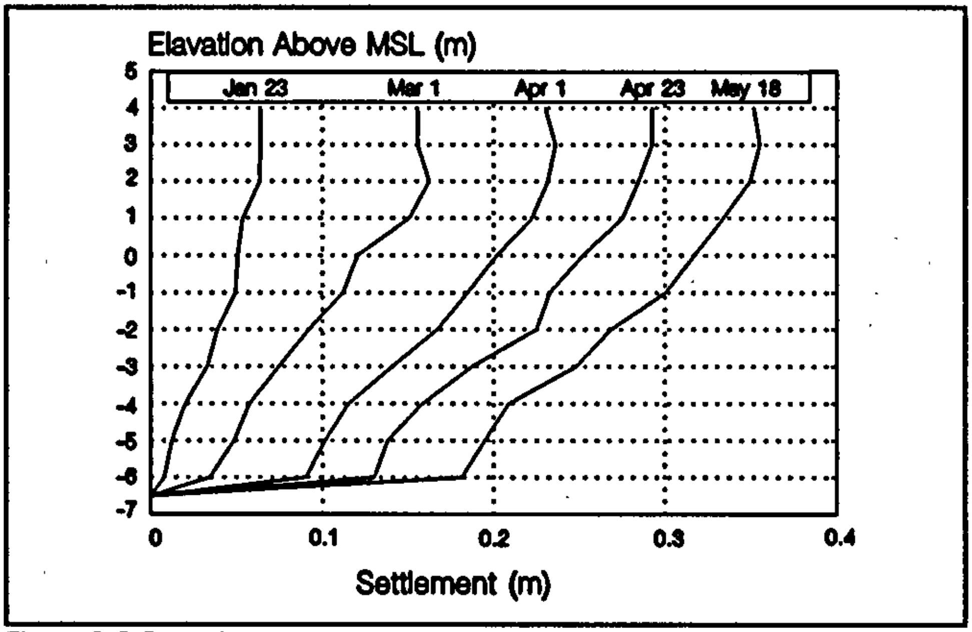


Figure 9.2 Spray ice settlement at Nipterk Island from 14 Jan through 18 May (Imperial Oil Ltd. 1991)

9.6 Spray Ice Temperatures

The purpose of spray ice temperature measurements is to ensure that thermal degradation of the spray ice as a result of drilling operations does not occur. It is possible that thermal degradation of the spray ice could cause foundation problems for the drill rig and cause a disruption of drilling activity.

At Mars Island 13 thermistor strings were installed around the island within the rig foundation and around the conductor.

At Nipterk Island six thermistor strings were installed. Spray ice temperatures were measured away from the drilling rig and camp buildings with an 11 m vertical thermistor string with its bottom bead placed one meter into the sea floor. Spray ice temperatures were monitored at the conductor and at a location 1.5 m from the conductor. In addition temperatures beneath the rig and warm buildings were also monitored.

At the Nipterk Island site temperature measurements were collected using a data acquisition and monitoring system. Temperatures in the critical areas around the conductor were monitored at a 30-second interval while temperatures in non critical areas were monitored hourly.

9.7 Meteorological Data

At both Mars and Nipterk islands meteorological data in the form of air temperature, wind speed and wind direction were recorded. This information is used in part for considering how meteorological factors influence island performance and how such performance might impact the drilling operation.

9.8 Stability Evaluation Program

Both Mars and Nipterk island were well instrumented and exceeded the requirements of the regulating agencies. Some data acquired as part of the island monitoring program is processed immediately through the data acquisition system. If any parameter exceeds a preset limit, action can be taken to remedy the situation.

In Canada, the factors governing winter operations in the Beaufort Sea are considered in terms of the Stability Alert Program, outlined in the Beaufort Drilling Contingency Plan. In the United States, drilling operations from spray ice islands are governed by agreement between the operating company and the Minerals Management Service which consists of a program proposed by the operator as the Critical Operations and Curtailment Plan.

Considering the measurement of the island, ice and weather parameters, in conjunction with real time data acquisition a reliable set of alert levels can be set. If any parameter exceeds a predetermined value, then the appropriate action can be taken.

In the case of meteorological factors, if wind speeds exceed historical values then consideration should be given to whether operations can be carried on safely. The results of extreme wind speeds may be reflected in ice pressure values, ice movement rates or in island movement as indicated by inplace inclinometers.

If air temperatures rise above freezing for extended periods of time, increased creep rates or island melting may result. These parameters will be reflected in measurements from settlement stations and from temperature monitoring equipment placed in the island.

If excessive heat is generated from the drilling operation or from camp operations this heat will be reflected as increased temperatures in the spray ice in the impacted area.

9.9 Summary

1. The degree and extent of monitoring required for spray ice structures depends on the location of the island, the type of operation being conducted and the environmental sensitivity of the operation.

2. Environmental driving forces such as ice movement and pressure may or may not be required. If the operations carried out have the potential of affecting the thermal environment of the spray ice, then spray ice temperatures at critical island locations should be monitored.

10.0 SPRAY ICE OPERATION AND ISLAND PERFORMANCE

Mobilization of equipment onto the spray ice island, carrying out the operational plan and performance monitoring are addressed in this chapter. By paying careful attention to the details of load placement and temperature monitoring no problems should be experienced operating from a spray ice structure.

10.1 Bearing Capacity

The ultimate strength of well prepared spray ice is quite high. Abele (1990) presents data for 657 kg m^{-3} dry processed snow that suggests the ultimate uniaxial strength is near 860 kPa. In this context we consider the ultimate strength to be the point at which the geometric structure of the snow collapses. For typical operations on spray ice, loads of this magnitude will occur only under the high pressures caused by wheeled loads.

Creep failure will be the governing mechanism for operations on spray ice structures . This type of failure will take place when the total creep, the creep rate, or the differential creep exceeds the ability of the equipment in use to accommodate it.
For a drilling rig the total settlement may be a major factor when preparing the foundation for the substructure. For a crane carrying out pile driving or excavation work creep settlement will not be a factor and higher ground pressures can be accommodated.

Data suggest that for applied ground pressures under 50 kPa creep of the spray ice will be about the same as for spray ice with no applied load. This phenomenon was discussed in the section on the creep of spray ice when we considered that there may be some applied stress levels below which the strain rate is independent of stress. It is possible that this stress level may be higher than 50 kPa. However, we have no data at this time to confirm this observation.

For most drilling rigs the ground pressure of the substructure will be considerably higher than 50 kPa. For example, a typical arctic class rig operating on the American North Slope may have a substructure base girder loading of 145 kPa. To reduce this pressure to a workable level the base girder load must be spread over a larger footprint to reduce the ground loading. This can be done using rigmats to spread the load.

Since there is limited data available on the creep of spray ice for large-scale structures it is prudent at this time to make every reasonable attempt to keep the loads on the spray ice to a minimum if the equipment involved in the operation is sensitive to settlement during its operation.

10.2 Temperature Considerations

As with creep settlement, maintaining the spray ice temperature at a predetermined value below freezing is important. Winter Arctic temperatures which are generally low will keep the near surface temperatures well below 0 °C. Beneath the surface of the island the temperatures warm to near the sea temperature as sea level is approached. The below water spray ice temperatures tend to be isothermal at the temperature of the sea water (near -1.8 °C). If the spray ice structure is constructed in fresh water or there is a fresh water layer in the water column then the below water spray ice temperatures will be closer to 0 °C.

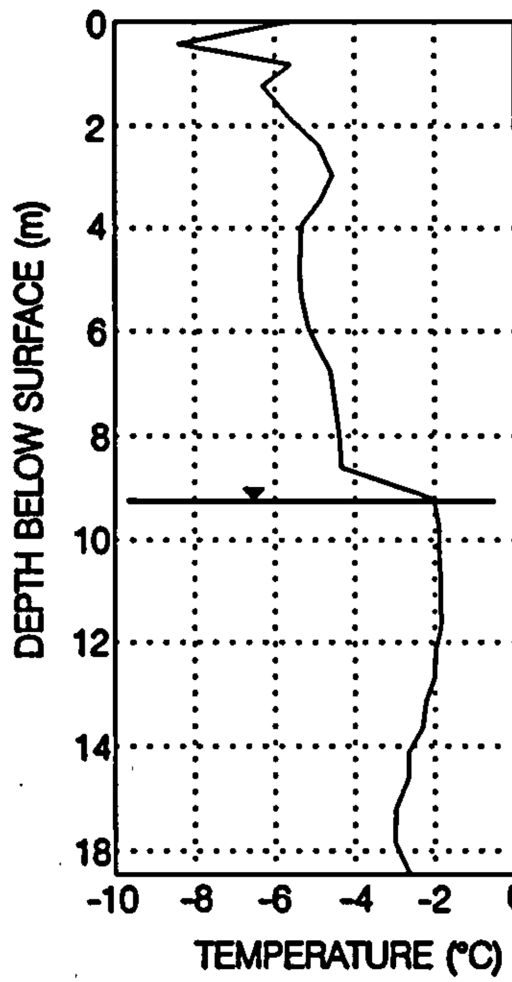


Figure 10.1 Spray ice temperature profile at Mars Island at the completion of construction (Amoco 1986)

Figure 10.1 is the temperature profile taken at the end of construction on 23 February 1886 at Mars Island. It is interesting to note the decrease in temperature in the at depths between 14 m and 18 m in this profile. The explanation for this temperature decrease is not readily apparent. A similar decrease in temperature can be seen in temperature data presented by Bugno et al. (1990).

Temperature considerations become important for spray ice in the area of the well bore, in and around the well cellar and under buildings and structures that generate a significant amount of heat. For Angasak Island a design surface ice temperature of -4 °C was used for calculating insulation requirements under structures (Weaver 1988). If temperatures exceed predetermined temperature levels remedial action must be initiated.

10.3 Well Cellar and Conductor

The most sensitive region of the island is in the vicinity of the well cellar and the conductor. At the well cellar working fluids can accumulate and drain into the supporting spray ice which will cause thermal erosion. Thermal erosion in this area might be critical since it is the region of highest island loads. Temperatures in and around the well cellar should be monitored on a regular basis. If fluids accumulate in the well cellar they should be pumped out as often as practical.

Possibly more critical than the well cellar is the well bore where it passes through both the above-water and below-water spray ice. At Mars Island the well bore temperature rose above 23 °C. This caused some melting of the spray ice around the conductor and required remedial action in the form of pumping sea water around the conductor to bring the temperatures under control. Mars Island did not use a refrigerated conductor but instead relied on the conductor being set in a culvert section to provide separation between the spray ice and the conductor.

At Angasak, Karluk and Nipterk Islands refrigerated conductors were used in an attempt to counter detrimental melting of the spray ice around the conductor. In general these proved effective. At Nipterk and Karluk some operational problems arose with the cooling systems and high temperatures were monitored in the vicinity of the conductor. Typically these thermal events were of short duration, and no structural problems were encountered. At Nipterk Island temperatures 1.5 m from the well bore showed no evidence of the increased temperatures.

In all instances where structural degradation of the spray ice took place around the well bore no changes were recorded in island performance. In part this can be attributed to the fact that ground bearing pressures were kept low, especially in the vicinity of the rig substructure.

10.4 Summary

1. When considering bearing capacity, crushing failure of the spray ice will take place when loads exceed ≈ 800 kPa. Loads below 150 kPa may cause an acceleration in creep rate, For island loadings below 50 kPa no increase in creep rates beyond the natural settlement is detectable.

2. Along with high bearing capacities, high temperatures will also increase the creep rate. As the temperature of the island becomes isothermal at 0°C both natural settlement and settlement due to imposed loads will increase.

3. Particular attention must be paid to keeping temperatures around the conductor low and not allowing warm fluids to leak through or accumulate in the well cellar. These fluids will not only warm the spray ice but may actually melt it. In the extreme case this could cause a structural instability in the island.

11.0 EXTENDED OPERATIONS

Spray ice exploration islands have performed well in both the Canadian and American Arctic. In addition spray ice has been effectively used to provide protection of structures from potentially damaging ice movements, and as a construction platform to build a permanent port facility. The use of spray ice structures has been conservative. Spray ice structures are built in relatively shallow water depths and operations from spray ice structures is completed well before any ablation of the spray ice takes place or break up of the sea ice occurs.

In this section we explore some possibilities regarding the potential for extending spray ice operations into deeper waters, extending spray ice operations later into the year, methods of removing spray ice and protecting spray ice from ablation. Some research and operational experienced have already addressed to these factors.

11.1 Other Spray Ice Production Methods

We have considered the primary and most important systems for producing spray ice. It is of some value to consider alternatives to these units that may be used in special operations.

11.1.1 Lightweight pumping units

The equipment for producing spray ice has been in general large and bulky. This is necessarily true when we consider the size of pumps required to produce flow rates of 10 to 60 cubic meters per minute, at relatively high pressures. Imperial Oil Ltd. (Weaver et al. 1992) constructed a heliportable system for producing spray ice. The purpose of building this unit was to provide a spray ice production system that can be deployed as soon a practical after landfast ice conditions are established. This unit was also designed to provide rapid repair of offshore floating ice roads, and river crossings.

The heliportable unit developed had a mass of 922 kg. The pump and diesel engine were mounted on a lightweight frame to which a 400-liter fuel tank was attached. The diesel engine used was a Cummins 4BT3.9P which powered a Monarch Industries NH4L15S end suction centrifugal pump. The output of the pump was 3.8 m^{3} min^{-1} with a working pressure of 965 kPa. The pump was used in conjunction with a WFR w/#3526 station monitor. A variety of straight stream nozzles were used with orifice diameters ranging from 39.37 mm to 48.49 mm. Water intake was from 25 cm holes drilled in the ice.

Operations with this system produced spray ice volumes of 5,000 m^{3} per day.

11.1.2 Off-site spray ice production

At times it is not possible to produce spray ice at the site of its final placement. This occurred in Nome, and the Red Dog Port Site when it was necessary to produce a volume of spray ice before the natural ice cover formed. Also when building linear structures such as a jetty spray ice placement may become a problem. At both the Nome and the Red Dog Port sites a stockpile of spray ice was produced on land. Immediately after freeze-up the stockpiled spray ice was moved onto the newly formed sea ice using standard earth moving equipment.

A front end loader with a bucket was used to load dump trucks, which then transported the spray ice to the site. The trucks were unloaded and bulldozers were used to place the spray ice. For this operation bulldozers up as large as a Caterpillar D-8 weighing 409 kN was used.

Utilizing this technique grounding of the spray ice was progressive. As the spray ice was deposited the overburden load would fail the natural ice locally. Spray ice deposited in this manner exhibited no difference from spray ice deposited directly from spraying.

At both the Nome and Red Dog sites temperatures were often above freezing, which precluded spray ice production. To augment the spray ice that was produced by normal methods snow gathered from drifts and snow removal operations was also used. At the Red Dog site several large oil storage tanks produced enough drifted snow to keep three eight cubic meter dump trucks operating 24 hours per day.

As with the spray ice produced on land, and transported to location, there was no detectable difference in the mechanical properties of naturally deposited snow and spray ice. We have discussed the reason for this. For snow or spray ice submerged below water the final product is nearly independent of the starting material. For above-water spray ice or snow, strength is derived from age hardening (sintering) and not as commonly believed from a freezing process. Mellor (1969) provides an in-depth discussion of processing dry snow for structural operations.

11.2 Spray Ice Survival

An area of fundamental interest in spray ice operations is how late in the season a spray ice structure can be used. Depending on the work being carried out we know that it is possible to carry on some operations on spray ice up to the point of the breakup of the natural ice sheet. We also know that in case of CIDS spray ice barrier at least a portion of it survived well into the open water season in September (Jahns et al 1986). Connoly (1986) carried out a theoretical investigation that suggested that a spray ice structure might survive through the summer season and into freeze-up. However, to date, no spray ice structure has survived a full open water season.

In terms of extended operations on spray ice, it is reasonable to consider operations on spray ice until the breakup of the natural ice sheet. At that time removing the equipment from the island with barges or other marine vessels.

For spray ice islands significant surface ablation begins when the average air temperature rises above freezing and rapid island disintegration takes place shortly after breakup occurs. The primary factors affecting the survival of spray ice structures into the summer season are ablation and wave erosion. If measures are taken to slow ablation and edge erosion the useful life of the spray ice structure can be increased.

11.2.1 Spray ice ablation

Experiments indicate that when insulating materials are placed on the surface of snow and spray ice the rate of surface ablation can be decreased considerably. Colbeck (1988) has addressed the topic of increasing snowmelt through albedo reduction and considers the effects of insulating layers on decreasing snowmelt. Poplin et al. (1991) carried out a series of experiments on Nipterk Island to determine the most effective agents in decreasing surface ablation.

In an experiment carried out between early May 1989 and the break up of Nipterk on 10 July 1989 they (Poplin et al. 1991) found that surface ablation could be decreased dramatically using insulating materials.

Table 11.1 presents the results of ablation tests using materials for insulating the island surface arranged in order of their effectiveness when compared to the unprotected spray ice. The overall result of the Nipterk ablation study indicates that if necessary the ablation of the island surface can be kept to a very acceptable minimum with proper insulation.

To carry out the Nipterk ablation test, plots were laid out on undisturbed sections of the island and different materials and thickness of materials were used to cover each plot. The various materials were placed on the island surface in April 1989 and were monitored until 5 July 1989. The island disintegrated in open water on 10 July. Figure 11.1 shows a plot of the island ablation versus time for selected materials of Table 11.1. As can be observed, little or no surface ablation took place prior to 25 May. Then surface ablation took place in a nearly linearly with time until the end of the test program.

The most effective agent for protecting the island surface were bags filled with sawdust. The bags used were 15 cm thick. The second most effective covering appeared to be 20 cm thick rig timbers. Unfortunately, during the study period the rig timber plot was destroyed so the results indicate an intermediate result. The third most effective covering was a layer of one cm of sawdust overlain with 5 cm of gravel. The above three materials were more than 90% effective at inhibiting ablation.

Table 11.2 Island ablation and protection offered by different insulating materials

Spray Ice Insulating Material	Ablation (cm)	Protection (%)	Spray Ice Insulating Material	Ablation (cm)	Protection (%)
None	229	0	Insulated tarp	49	79
Sawdust bags	5	98	0.3 m gravel	66	71
Rig timbers	8*	96	1.5 cm sawdust	80	65
1 cm sawdust, 5 cm gravel	20	91	Rufco sheet	84	63
1 m gravel	25	89	1 cm Sawdust	107	53
2 cm sawdust	30	87	0.4 kg Nylon	125	45
0.6 m gravel	35	85			

* Rig timbers were destroyed prior to the completion of the test. Values represent last recorded

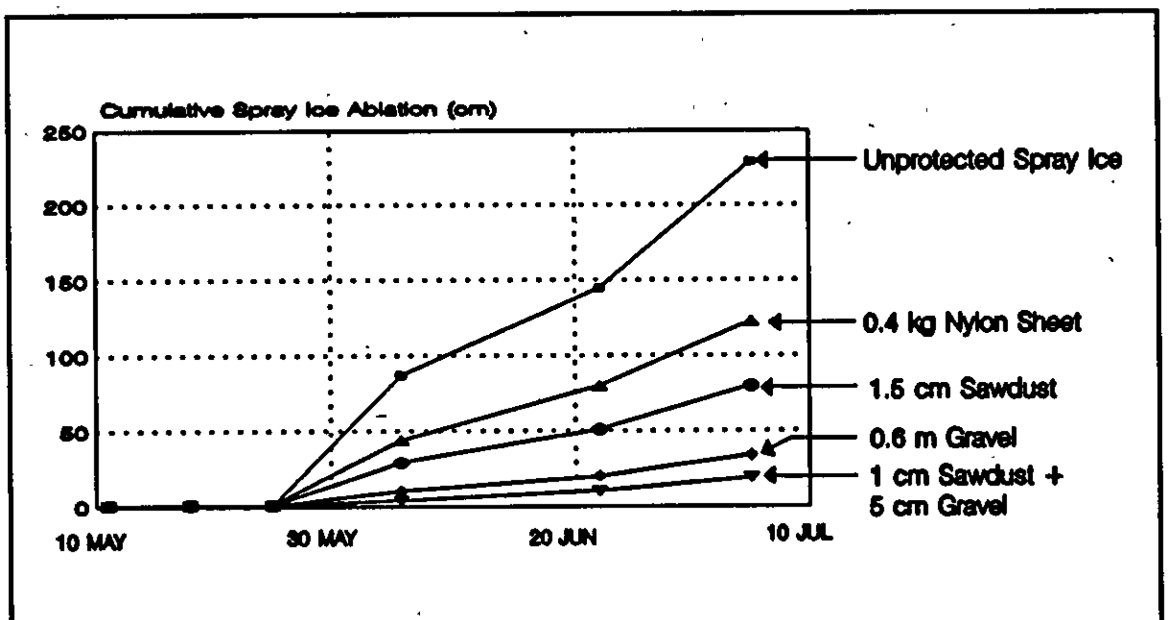


Figure 11.1 Spray ice ablation as a function of time for selected materials.

Insulating materials used on spray ice structures may have to satisfy two functions. The first is to prevent surface melting and the second is to provide a trafficable surface. Sawdust bags will provide surface protection but not a trafficable surface. Rig mats or timbers, or gravel overlying sawdust will provide both insulation and a surface over which heavy equipment can operate. Using rig mats in conjunction with a solid foam insulation would also provide significant insulation along with a trafficable surface.

11.2.2 Island erosion

A more important factor than erosion in determining how long an island will survive in the summer season is erosion of the edge of the island during the open water season. Although portions of the spray ice barrier at the CIDS Antares site lasted into September, spray ice islands with their modest volumes and low freeboard tend to disintegrate quite rapidly once breakup takes place.

At Karluk Island, which was not protected in any way to mitigate ablation, disintegrated under the action of sea forces within 2.5 weeks of the breakup of the landfast icesheet in the absence of any significant storms (Poplin et al. 1991). At Nipterk the breakup of the landfast ice took place on 24 June. On 5 July about 28% of the island had been lost due to edge erosion. By 8 July the island was reduced to 64% of its original size and final disintegration of the island took place on 10 July, 16 days after the breakup of the landfast ice.

The mechanism of island edge erosion is primarily one of thermal wave erosion. In this mode of island disintegration, wave action produces high local water velocities resulting in a high effective heat transfer rate between the near-surface water and the spray ice edge. Wave induced heat transfer tends to undercut the island edges creating notches. As the notches grow inward at the waterline, spray ice overhangs and underwater terraces are created. In time, the overhangs collapse due to gravity forces and the underwater terraces either break upward because of buoyancy or disintegrate in place, depending on the cohesion of the seabed.

For low-lying islands such as exploratory drill pads, after significant ablation has taken place the islands can also break up due to insufficient freeboard. At Nipterk Island (Poplin et al. 1991) the freeboard on unprotected areas of the island was reduced to 0.5 m to 1.0 m. At Nipterk small sections of the island tended to lift off the bottom and drift away under the action of wind waves and currents.

As a means of mitigating island edge erosion an experiment was conducted a Nipterk to see if island edge erosion could be reduced (Poplin et al. 1991). In this experiment impermeable sheets and a net were placed near the edge of the island. It was found that the impermeable sheets were effective in reducing edge erosion. Overall, no difference was found in the different sheets used to protect the island edge. All sheets appeared to be more effective than the net.

11.3 Spray Ice Removal and Excavation

Extending the life of spray ice structures is important under some conditions however, there are instances where it may become important to remove spray ice before it would naturally disintegrate. For example, the spray ice barriers constructed at Nome were used to protect a gold dredge (Bima) and its supporting work boat (Aquamarine). For each day that the gold dredge remained inside the spray ice barrier after the onset of open water, revenue was lost.

Methods used to remove the spray ice around the Bima and Aquamarine consisted of eroding the spray ice with high pressure water monitors, removal of the spray ice with backhoes and draglines and wheel-washing it away with the tug Aquamarine. Of the three methods tried the use of the tug Aquamarine was by far the most effective.

Attempts to remove the spray ice by directing high velocity water at the barrier produced only marginal results. The water stream quickly cut a hole or slot in the spray ice. However, the effect was very localized. Several days of trials proved this technique unsuccessful in clearing away large quantities of spray ice.

The second method of spray ice removal was with the use of ordinary excavating equipment. Using backhoes and a dragline attached to a crane a large quantity of spray ice was excavated. Although this method was effective it was a slow process. Excavating equipment is useful where it is necessary to remove spray ice selectively, i.e. to remove spray ice around structures and to contour the side slopes of spray ice for loading and unloading vessels.

In general spray ice offers little resistance to excavation. This is especially true in the upper layers of the material. It is difficult to remove the natural sea ice layer that is anchored at the base of the spray ice structure. At Nome the seaice was bonded firmly to the seabed and was difficult to break loose with backhoes and draglines. The most successful method found for removing the sea ice layer was to remove the spray ice overburden. With enough of the overburden removed, the base layer would eventually break loose and float to the surface. The time it took for the sea ice layer to break loose was often several days.

For fast and efficient removal of spray ice, wheel washing the spray ice with the tug was by far the most effective method. The tug Aquamarine is 56 m in length and has a beam of 12 m. It has three propellers and is rated at 5,700 horsepower. To remove the spray ice the stern of the Aquamarine was attached to a hawser that was tied to a piling. The tug worked back and forth while its prop-wash was directed at the spray ice. In a period of eight to ten hours, 150,000 m^3 of spray ice were removed.

While wheel-washing the spray ice, the propellers operated at relatively low rpm with the boat's engines operating just above idle speed.

The exact mechanism by which wheel-washing removes the spray ice is not understood. It appears to be a combination of the erosive effects of the water on it and the thermal degradation of it. Failure of the spray ice takes place when the below-water material is sufficiently undercut and the above-water portion of the spray ice collapses and is washed away. The submerged spray ice material then breaks off and floats to the surface due to buoyancy effects. Using this technique there appears to be no problem removing the bottom layer of natural ice as was experienced with standard excavation methods.

11.4 Operating on Narrow Spray Ice Structures

On spray ice islands heavy equipment is placed in the center of the island and there is little chance to observe how the spray ice might react if the load is placed close to the edge of the spray ice. Operations at the Nome spray ice barrier and the Red Dog Port Site Jetty provided us with experience in this regard. Unlike spray ice islands the spray ice structures at Nome and Red Dog were relatively narrow structures. Experience at the Nome and Red Dog sites indicated that spray ice has substantial strength.

The spray ice jetty at Red Dog had a design working surface 15 m in width. The largest piece of equipment to be moved over the jetty was a Manitowok model 4100 Series-2 crane. With the crawlers extended the width of this unit was 6.4 m. The mass of the crane was 228,000 kg. The ground pressure exerted by the unit was 130 kPa. In addition to the dead-load weight, it was determined that the maximum loads would be exerted during pile extraction operations. While operating the crane was positioned close to a 5 m vertical spray ice face.

To reduce the ground pressure while the crane was in operating position the crane was placed on timber mats. These mats lowered the ground pressure by a factor of three to 43 kPa. The crane was located on a raised spray ice platform that was constructed by dumping dry snow into position and reworking it with a bulldozer. The material was allowed to sinter for several days before the crane was placed on it.

11.5 Deeper Water Operations

Spray ice has proved very successful in operations in the landfast ice zone. Since spray ice is attractive from both an environmental and cost of construction standpoint there is some interest in constructing spray ice structures in deeper waters at the edge of the landfast ice.

Weaver et al. (1991) has addressed the construction of spray ice structures in deeper water. They note that the feasibility of on-ice construction techniques is limited to the nearshore areas. Faster construction methods are required in order for spray ice islands to be built in the outer regions of the landfast ice zone.
Spray ice islands could be completed earlier in the winter season using the following approaches.

- larger capacity pumps
- early construction starts

- decrease required spray ice volume

The optimal pumps for early season on-ice operations are light weight mobile units. Large pumps used on floating ice cover require that the ice cover be thickened. However, large pumps mounted on ice breakers or grounded platforms are very effective. Over two million cubic meters of spray ice were placed at the CIDS Antares site in 60 days. Off-ice spraying can start as soon as an ice cover forms and the temperatures drop below -15°C.

Spray ice volume requirements can be reduced either by generating rubble at the site during freezeup (Gulati et al 1990, Potter et al. 1982, Goff et al. 1986) or by reducing the diameter of the island. The most promising way of reducing the required island diameter is to increase the sliding resistance by enhancing the seabed strength.

The technology for constructing spray ice structures in 16 m water is feasible. However, there are some hazards associated with spray ice construction in the outer region of the landfast ice zone. The primary hazard is that a mid-winter ice movement will occur leaving the island in open water. In this event the island would have to be evacuated.

11.6 Summary

1. Spray ice production is can be enhanced in the early season by using lightweight pumping units. If temperatures are such that spray ice production is not possible snow can be substituted if an abundant supply is available. It is also feasible to produce spray ice at one location and move it to the construction site.

2. Results of using insulating materials on spray ice surfaces has proved very effective. With effective insulation spray ice ablation can be kept to a minimum.

3. An important factor in the survival of spray ice structures into the open water season is protecting the edge of the structure from wave erosion. Initial tests indicate to some extent this is feasible.

4. Spray ice can be removed with standard excavating equipment. However, wheel-washing with marine vessels is a far more effective method for spray ice removal.

5. Narrow spray ice structures have been used effectively and have shown that if a conservative approach is taken heavy equipment can be operated near the edge of the spray ice.

6. The technology currently exist to build spray ice structures in water depths of 16 m or more. However, all the risk associated with this type of operation must be evaluated.

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