Abstract
This paper describes the engineering aspects of preparing the Ohmsett tank for the testing of a skimmer in brash ice conditions. The paper details: the analyses done to determine the types and sizes of ice that could be used for testing; the sourcing of the ice, and its transportation, storage and placement in the tank; and, the modelling of heat transfer in the tank and the cooling of the water to maintain the ice conditions.

1 Introduction
Interest was expressed early in 2001 in extending the capabilities of Ohmsett to include testing of spill response equipment in realistic ice conditions. In particular, there was a desire to quantitatively test the oil recovery performance of the prototype Mechanical Oil Recovery in Ice (MORICE) skimmer in representative sea ice in January 2002 (see Jensen et al. in these proceedings). The objective of the study reported here was to plan and engineer techniques and systems for implementing testing of skimmers in brash ice conditions at Ohmsett. More specifically, the goal was to develop the capability to quantitatively test the oil recovery performance of the prototype MORICE skimmer in realistic brash1 ice.

Ohmsett, a 10-million litre salt water test tank near Atlantic Highlands, NJ, is a location that does not favour the growth of ice in the winter. A detailed review of meteorological data from the area revealed that the probability of conditions that favour the growth of thin ice (ca. 2 cm) in winter at Ohmsett would seem to occur three years in five, or a probability of 0.6. The probability of thicker ice (ca 20 cm) developing would seem to be one year in five, or 0.2 (Buist, 2001). In order to conduct realistic testing in brash sea ice conditions at Ohmsett it was necessary to import the ice and cool the tank.

2 Assessment of Requirements for Test Ice.
This first task in the study involved defining the desired characteristics of various test ice fields. Issues such as ice salinity, properties, dimensions, size distribution and concentrations were addressed to cover a wide range of possible pack ice spill situations, with an emphasis on those desired to test the prototype MORICE skimmer. Differences between pack ice characteristics at freeze-up and break-up were

---

1 Brash ice, also known as small ice cakes, is defined by the Canadian Ice Service as being less than 2 m (6.6') in width.
also reviewed. The issue of whether or not freshwater ice or artificial sea ice could be used as an acceptable substitute or supplement for sea ice was also addressed.

Based on a review of the physical dimensions and capacities of the MORICE skimmer, the following basic criteria for the test ice fields were developed:

1. Two ice field sizes, one 4.9 m x 76.2 m (16' x 250'), and one 19.8 m x 76.2 m (65' x 200');
2. Ice concentration of 9-tenths;
   - Maximum piece size 1.2 m x 1.2 m x 20 cm (4' x 4' x 8''), based on the skimmer characteristics;
   - Properties similar to level, first year sea ice grown naturally in near-shore waters.

A quick review of the differences in physical characteristics and oil/ice interactions between sea ice and freshwater ice (e.g., porosity and crystal structure) quickly eliminated freshwater ice as an option for the testing.

Next, the characteristics of artificially grown model ice and sea ice were compared, to determine if there were any advantages to either.

1.1 Model Ice

Saline ice was first used in model testing at the Arctic and Antarctic Research Institute (AARI) in Leningrad (St. Petersburg) in the late 1950's. This ice had salinities in the range of 10-20 ppt, higher than natural sea ice (typically 8-9 ppt for 30 cm first-year ice grown in 34 ppt seawater). The Russian method of rapidly freezing saline water was used extensively in ice basins around the world in the 60's and 70's because of its convenience and low cost.

Problems arose when it was found that simple model ice grown in this fashion had insufficient elasticity relative to the flexural strength. In addition the straight salt solution was extremely corrosive. The use of lower salt concentrations and warmer temperatures improved this ratio but led to other complications such as 'waterlogged' ice where the bulk density was too high and as a result, the freeboard too low.

In an effort to better duplicate the desired strength scaling and elastic/flexural ratios Timco (1979) investigated the properties of ice grown with various chemicals added to the water to alter the properties of the sheet. Tests of over 40 dopants resulted in the selection of carbamide (urea) at a 1.3% concentration. Ice grown from this solution possessed good strength and rigidity characteristics and was nontoxic. One drawback was that it has a slight corrosive action on concrete but was still much more favourable in these respects than a pure salt solution.

The literature contains the results of extensive tests on the physical properties and structure of both saline-doped and urea-doped ice (Timco, 1980 and 1986; Hirayama, 1983). Urea doped ice is now used in the majority of refrigerated model basins in North America and Europe. This ice consists of a mechanically hard upper layer, a thin transition region, and a lower columnar region, which forms the majority (75%) of the thickness. The urea-doped ice reproduces friction coefficients (ice-steel) quite well (typical value of 0.35). Both types of model ice have comparable densities in the range of 0.93 to 0.94. In comparison, typical sea ice densities range from 0.89 to 0.92. The Institute of Marine Dynamics (IMD) in St. John's, Newfoundland introduces air bubbles into the model ice to reduce the density to about 0.90. This is done with a tube with tiny holes, containing air under pressure, traversing the bottom
of the tank while the ice grows. The air bubbles rise and get trapped into the ice sheet. This procedure works well but tends to be difficult to adjust and would not be justified for the MORICE test program.

In the late 80's, researchers at NRC developed a new type of doped ice grown from a solution of three different dopants - ethylene glycol, aliphatic detergent and sugar. This so-called EGADS ice is single-layered, fine-grained and strictly columnar throughout its thickness. In terms of correctly modelling the important strength parameters, this ice is considered quite superior to urea model ice but at much higher cost. (Timco, 1986).

The overall procedure for making model ice is similar at different facilities. The urea solution is precooled to approximately +2°C. The air temperature is then lowered to between -15 and -20°C, at which time an ice cover begins to form naturally. This ice is skimmed off and the refrigeration shut off. A fine spray mist is introduced to seed the surface, forming a fine crystalline pattern with small grain sizes. Refrigeration is restarted and wind deflectors are lowered to keep the surface completely quiescent. A rapid transition layer from random to horizontal C-axis orientation occurs within approximately 1 cm depth. At this point the wind deflectors are raised in increase the heat transfer and 4-5 cm of ice is achieved within 8 hours. Further growth takes much longer, for example 20 to 25 cm in 4 days at CRREL.

For ice sheets intended for modelling interactions with vessels and structures, a warm-up period (air temperatures maintained just below freezing) is used to control the eventual strength properties of the desired model sheet. During this tempering process the brine pockets in the ice not only drain but also enlarge at the same time. The resulting ice has favourable properties for model testing but suffers from being excessively weak in flexure for cutting, lifting and transport. Without the need to correctly model the scaled strength, the tempering part of the ice growing process was deemed unnecessary and the model ice could be harvested directly at colder temperatures (e.g., -10 to -15°C). In this manner, the ice would be stronger to resist breakage while being lifted and moved.

1.2 Natural Sea Ice

The primary differences between the various types of model ice and natural sea ice depend on the surface conditions at the onset of freezing in the ocean and the subsequent growth rate. In nature, once the surface waters have cooled to the freezing point (nominally -1.9°C for 35 ppt seawater) and the air temperature remains below -2°C, the first small crystals of frazil ice form and float on the surface. These initial crystals can be up to a few centimetres across under conditions of slow growth characteristic of temperate sub-arctic areas. Such crystal sizes are considerably larger than the grain sizes normally achieved at the surface of seeded model ice. For the purposes of the Ohmsett tests, this difference would never be noticed in terms of skimmer performance or oil in ice behavior.

The progression of the early ice forms from slush (frazil nucleated by snowfall) to grease, ice rind, and perhaps pancakes, depends very much on the degree of agitation of the sea surface. Under extremely quiescent conditions, the new ice sheet will quickly progress from a thin upper layer of primary ice where the crystals have a random C-axis orientation to the secondary ice, which makes up the bulk of the sheet. This ice is columnar-grained with the crystals having a preferred horizontal
orientation. Liquid brine exists in pockets between the crystals. These pockets extend vertically through the sheet and create pathways for rapid drainage of the trapped brine when the ice is warmed. This type of structure is essentially identical to that obtained with urea-doped model ice.

The amount of brine trapped during the freezing process depends on the growth rate at the time of formation and generally falls in the range of 4 to 8 ppt (rapidly growing ice traps more salt while slower growing ice at depth is more efficient in rejecting salt as it thickens). Thicker sheets have lower average salinities. Typical salinity profiles for 20 to 30 cm sheets grown in the Arctic show a bell shaped curve with 9-10 ppt at the surface and bottom and 8-9 ppt in the center. Ice sheets grown in a more temperate climate like the Gulf of St Lawrence will likely display lower salinities in the 4 to 6 ppt range, reflecting the slower growth rates. There is a gradual decrease in salinity with time through the winter in a natural ice sheet amounting to about 0.5 ppt per month; at the thickness values being considered in this project, this process is not a factor.

The process of brine drainage within the natural ice sheet increases rapidly as temperatures warm. For example, above -15°C, brine cells tend to be interconnected, with the result that the brine can quickly drain away under the influence of gravity (the same as in model ice removed from a basin). Approaching the melting point, brine drainage accelerates, and the ice becomes progressively more porous with a corresponding increase in bulk density as water fills the channels in the ice through capillary action.

Brackish ice grown in coastal areas with lower water salinities can freeze at different rates from normal sea ice. For example, normal seawater (salinities higher than 24.7 ppt) becomes progressively denser as its temperature drops to the freezing point. In contrast fresh water has an anomalous maximum density at +4°C. This difference explains why fresh water ice forms more readily than sea ice (the density anomaly leads to a stable layer of cold, light fresh water with no convective mixing with lower levels). In contrast, seawater is constantly sinking as it cools. In order to obtain "realistic" sea ice it is recommended that sites influenced by substantial freshwater inflow (estuaries) be avoided.

Deformation features occur with natural sea ice, which are not normally experienced in the model basin. Even in calm nearshore areas, the new ice is often moved about by wind stress, leading to rafted layers in the upper surface. Heavy snowfalls soon after freeze-up can depress the new ice and cause flooding and re-freezing (so-called superimposed ice). Freezing rates are highly variable according to temperature conditions at the time and the presence or not of an insulating snow layer. All of these factors lead to a highly variable ice sheet in terms of its crystal structure, trapped air pockets and salinity.

In summary, there are differences between model ice and natural sea ice. These differences are related to the variable growing conditions experienced in nature contrasted to the uniform, controlled conditions in the model basin. Model ice has a very thin transition region of randomly oriented crystals near the ice surface while natural ice may have multiple layers of superimposed snow ice and rafted layers of randomly oriented crystal structure before reverting to the typical columnar structure at depth.

The grain sizes of model ice and natural ice are likely to be different, with the
model ice tending towards a finer grained structure than sea ice grown in temperate conditions typical of the Canadian Maritime provinces. As a result, the salinity of model ice could exceed that experienced with ice in the Gulf of St. Lawrence, depending on temperature conditions at the time of formation. In practice, these differences only apply to the top 5 cm of the ice. Once a sufficient thermal barrier is established, large variations in ambient air temperature have a lesser effect on the ice salinity.

In general, model ice probably comes closer to mimicking Arctic first year sea ice than temperate sea ice found in sub-arctic areas. This difference is important for model testing where it is essential to match the scaled strength characteristics of the real ice cover, but not for the MORICE tests. The only strength related factor, which may be important, concerns the inherent structural weakness in model ice compared with natural sea ice (Timco, 1981). This reduced strength could affect the handling, transport and preparation and maintenance of the desired floes or blocks. As explained above, harvesting the ice at cold temperatures, rather than tempering the sheet at close to the freezing point for a conventional model test can easily overcome this potential drawback.

Both types of ice (model or natural) consist mainly of columnar ice with an established vertical network of brine channels, which react in a similar manner as the temperature is raised. In this respect there should be little difference in porosity between model ice and natural ice once it has been transported to the site.

Both types of ice have similar bulk densities (natural ice could trap more air bubbles and potentially have a slightly lower specific gravity), and friction characteristics (ice to steel).

Model ice has a uniform and repeatable physical structure without the variability which occurs in natural sea ice as a result of unpredictable climatic factors. Model ice will closely mimic real ice grown under calm conditions nearshore with minimal wave action and steady temperatures. However there will be many situations where the natural ice is far less homogeneous in terms of internal structure. For the purposes of these tests it was concluded there was no physical difference between model ice and natural sea ice that would have an appreciable effect on the results.

2 Determining Where to Obtain Sea Ice

The next task was to find a source of sea ice and plan how to harvest it, package it, ship it and store it at Ohmsett until it was needed in early January, 2002. There are two potential sources of sea ice in reasonable proximity to the Ohmsett test basin:

1. Ice grown in urea-doped water at the U.S Army Corps of Engineers Cold Regions Research and Engineering Laboratory (CRREL) facility in Hanover NH; and,
2. Natural ice harvested near-shore along the New Brunswick or Nova Scotia coast in the Gulf of St. Lawrence, Canada (the preferred location would depend on logistics, ease of access, desired ice characteristics, local infrastructure etc.).

2.1 Potential Natural Sea Ice Sources

A survey of sea ice growth in areas with highway access to Ohmsett was
undertaken to determine whether an economical source of natural sea ice for the MORICE testing program in early January could be found. A minimum ice thickness of 20 cm (8 inches) was used as a criteria. Figures 1, 2 and 3 show the 30-year median sea ice concentrations in January for the eastern seaboard of North America, stretching from New England to Labrador. Traditionally, there is no sea ice growth south of 45°N by the end of January. By early January, ice growth in the bays along the eastern coast of New Brunswick on the Gulf of St. Lawrence and Northumberland Strait (the body of water between New Brunswick and Prince Edward Island) is well under way and the coverage is usually 10/10ths.

There are ice thickness measurement data sets available for two sites in the vicinity of the eastern coast of New Brunswick: one for Caraquet, located on the southern shore of the mouth of the Baie des Chaleurs, and one for Summerside, PEI, on the northern shore of Northumberland Strait, across from New Brunswick. Figure 4 shows the ice thickness data from Caraquet for the years 1974 through 1986. The historic probability of the ice being at least 20 cm thick by the end of the first week of January is 0.65 (7/11) at Caraquet. By mid-January of almost all years (11 of 12) the ice is at least 20 cm thick. Also shown on Figure 4 is the snow cover on the ice. In most years the snow is less than 10 cm thick by mid-January, although it would be necessary to clear some snow from an ice sheet before it could be harvested.

Figure 5 shows the ice thickness data for the years 1974 through 1978 at Summerside. Note that the date associated with the grid line on the graph for this data is one week earlier than for the Caraquet graph. The historic probability of the ice being at least 20 cm thick by the end of the first week of January is 0.6 (3/5) at Summerside. By mid-January, the ice at Summerside was at least 20 cm thick 4 years out of 5.

There appear to be a number of areas along the eastern coast of New Brunswick that would have suitable thicknesses of sea ice available for harvesting in mid-January. A review of the Sailing Directions (aka the Pilot) for the Gulf of St. Lawrence (Canadian Hydrographic Service, 1992), indicates that there are about a dozen possible locations along the eastern shore of New Brunswick that could be used to harvest sea ice. The best of these appears to be Shediac, NB. Shediac is near Moncton, a major city and is on the Trans-Canada Highway offering excellent transportation access.

2.2 Comparison of Ice Source Options

The driving distance from Shediac, NB to Ohmsett is 1240 km (771 miles), an estimated driving time of 15 hours, 24 minutes. It should be noted that sea ice shipments from Shediac, NB would have to clear US Customs at the Canada/US border. In comparison, the driving distance from CRREL in Hanover, NH to Ohmsett is 495 km (308 miles), with an estimated driving time of 5.5 hours. A rough estimate of the cost to mine sea ice at Shediac indicated that this option, including transportation, would be about one-half that of ice from CRREL. For a variety of reasons, primarily certainty of supply given the need to have the ice at Ohmsett in early January, the CRREL facility was chosen to provide the ice. In retrospect, particularly in light of the exceptionally warm winter experienced by much of the eastern seaboard in 2002, this was the correct decision.
3 Test Ice Floe Sizes

In the way of background, there is a precedent for creating brash ice at Ohmsett. Smith and Diaz, (1987) describe burning tests in "broken" ice in the tank where the ice field was enclosed by a rigid wooden boom with outside dimensions of 5.8 m x 7.3 m (19 ft x 24 ft). Within this enclosure were placed 140-kg (300-lb) fresh water ice cakes with typical dimensions of 0.5 x 1.1 m x 0.2 m (1.8 ft x 4 ft x 9 inches). Apparently, wooden spacers were placed in the tank to maintain a clearance of 2 to 5 cm (1 to 2 inches) between the ice cakes.

For practical reasons of harvesting, shipping and processing it was determined that three different ice sizes were reasonable to make up the brash ice field at Ohmsett:

- the originally harvested 1.2 m x 1.2 m (4 ft x 4 ft) block size (arrived at by considering both the maximum individual slab weight for handling and the maximum block size which can be realistically processed by the MORICE prototype skimmer) - denoted as F1
- some subset of these parent blocks - most simply viewed as splitting them into four 0.6 m x 0.6 m (2 ft x 2 ft parcels) - denoted as F2
- background brash and fragments under 10 cm (4 inches) which often cover a large proportion of the ocean surface in a pack ice situation - denoted as F3

The question arose as to what proportion of each size range was realistic (i.e., most closely matches natural conditions in terms of the relative amounts of ice in each size category). In order to arrive at a suggested floe size distribution for the MORICE tests, three previous spills in ice (two experimental and one accidental) were examined using vertical or near-vertical aerial photographs published in reports:

1. A Norwegian 1993 experimental spill in pack ice (Vefsnmo and Johannessen, 1994). They characterized the ice cover as 80-90% concentration overall, of which 15-25% by area was new ice (brash, frazil, grease and slush). It is reasonable to assume that this new ice was typically made up of chunks and fragments less than 10 cm (4 inches).

2. A Canadian 1986 oil-in-pack ice experiment reported by SL Ross and Dickins (1987). Figures 28 and 30 in the project report clearly show a broad mix of floe sizes with a large percentage of brash and slush in the water. The overall ice concentrations in the areas of the photographs used for a simple estimate of floe size proportions were in the range of 8-9/10, very similar to the Norwegian test.

3. An accidental spill of heavy oil from the tanker Kurdistan off the Canadian East Coast in 1979. C-CORE (1980) documented the ice conditions surrounding this incident in detail. Figure 8-30 of their report shows a clear view of floes typically 5 m in diameter with slush and brash and smaller ice cakes between.

Each of these case studies was used to determine the relative proportions of F1, F2 and F3 using relative scaling to normalize the maximum floe size category in each picture against an assumed 1.2 m x 1.2 m parent slab (in other words, the actual scales of the pictures were altered make the maximum floe sizes consistent between all the field situations).
The results were interesting in that they showed a distinct difference between the 1986 ice conditions and the other two cases. Both the Norwegian 1993 experiment and the 1979 Kurdistan report provided identical results with a typical distribution from large to small as .55/.27/.18 (18% by area in small fragments). In contrast, both of the take-offs from the 1986 results showed a very different distribution of about .23/.23/.54 (54% in small fragments and slush).

Given that the primary purpose of the MORICE testing was to examine the ability of the device to clean oil from individual floes, there seems to be little point in working with an ice field, which is 50% or more, comprised of slush. Also the survival time of these very small ice fragments in the tank could be quite short if the tests had to be conducted at near freezing or just above freezing temperatures.

Based on this fairly simple approach, a reasonable mix of ice sizes for the test program would follow distributions similar to the 1993 and 1979 spills, that is on the order of 55% as 1.2 m x 1.2 m (4 ft x 4 ft), 25-30% 0.6 m x 0.6 m (2 ft x 2 ft) and 15-20% small fragments and slush.

4 Ice Harvesting, Packaging, Shipping and Storage

The ice obtained from CRREL was harvested using the following procedures. If the ice had been obtained from a natural source, similar techniques could have been used. It required four to five days to grow each sheet of ice in the CRREL Ice Engineering Basin (37 m x 9 m x 2.4 m deep - 120 ft x 30 ft x 8 ft) to a thickness of 20 to 25 cm. When the sheet reached the desired thickness it was cut with electric chainsaws into 1 m x 1.2 m slabs weighing in the order of 220 kg (480 lb) each. The slabs were cut smaller than 1.2 m x 1.2 m to allow two slabs to fit easily beside each other inside a 2.4-m wide road trailer. Once cut, the slabs were lifted by a specially-designed platform attached to the moving overhead crane in the CRREL facility (Figure 6) and transferred to pallets. A layer of plastic sheeting was placed between the slabs to prevent their bonding together. Plastic banding was then used to secure the stack of slabs to the pallet. Each sheet of ice grown in the CRREL basin generated about 250 slabs of ice - filling about 65 pallets.

The pallets were loaded onto refrigerated tractor trailers for transport to Ohmsett. Using 45,000 lb as typical highway load limit for a refrigerated semi-trailer rig, a full load consisted of approximately 22 pallets. Each sheet of ice grown at CRREL filled three refrigerated semi-trailers. Forklifts able to drive inside the trailers were used to load the pallets.

On arrival at Ohmsett (beginning in mid-December 2001) the pallets of ice were taken off the trucks with forklifts (Figure 8) and placed in refrigerated ISO containers for storage (Figure 9) until they were needed. The storage containers were maintained at a temperature of -15°C (5°F).

5 Cooling the Ohmsett Water

In order for testing in brash ice conditions in Ohmsett to be feasible, using either natural or artificially grown sea ice, the temperature of the 9,840 m³ (2.6 million gallons) of tank water had to be maintained below a maximum of 0°C (32°F) (above this temperature the ice will melt very rapidly) and above -1.7°C (29°F) (the
freezing point of 35 ppt salt water). Ideally the water should be in the -1 to -0.5°C (30 to 31°F) range, to preserve a test field of sea ice for as long as possible. A review of climatic records from nearby coastal locations compared to available Ohmsett tank water temperatures indicated that a good indicator (generally within 2°C, or 3°F) of the tank water temperature was the weekly average air temperature. Using this indicator and recent detailed meteorological records from a nearby location, it was determined that the tank would cool to the required temperature range only occasionally, specifically three two-week periods during the months of January and February over the last five years for which detailed records existed. In the same period there were many warm spells during the winter months when the water temperature would exceed 4.5°C (40°F). It was clear that it would be necessary to artificially cool the tank water, and maintain it in the desired temperature range, in order to be able to maintain a test ice field.

In order to estimate the amount of cooling that may be needed in order to maintain the Ohmsett tank water temperature in the -1°C to -0.5°C range and to provide an operational tool to predict daily tank water temperature changes based on long-range weather forecasts, a heat transfer model of the tank was derived. Figure 10 shows the basis for the model. The heat transferred to/from the tank is the sum of solar radiation, re-radiation from the water to the sky, heat losses/gains from evaporation/condensation, convective heat gains/losses due to wind, conductive heat losses to the ground and heat gains/losses from precipitation falling on the water in the tank.

\[ Q_{\text{total}} = Q_{\text{conv}} + Q_{\text{evap}} + Q_{\text{condense}} + Q_{\text{precip}} + Q_{\text{solar}} + Q_{\text{rerad}} + Q_{\text{conduct}} \] (1)

The rate of change in tank temperature is related to the heat gained or lost through:

\[ Q_{\text{total}} = mCp\Delta T/\Delta t \] (2)

Where: 
- \( Q_{\text{total}} \) = net rate of change in heat content of water [J/hr]
- \( m \) = mass of water in tank (assumed well mixed) [kg]
- \( = 10 \times 10^6 \) kg
- \( Cp \) = heat capacity of seawater [J/kg°C]
- \( = 4 \times 10^3 \) J/kg°C
- \( \Delta T \) = change in water temperature [°C]
- \( \Delta t \) = time period over which temperature change occurs [hr]

Two modes of heat transfer were determined to be negligible: conduction and precipitation. Heat conduction to in-ground pools was reported to account for less than 10% of total measured heat transfer (Jones et al., 1993) and is ignored for these purposes. Rough calculations indicate that each inch of rain that is 10°C warmer than the water, would only raise the tank temperature by 0.1°C, certainly negligible for these purposes. Each centimetre of snow would cool the tank contents by only 0.03°C, again negligible.

Empirical equations for the other various modes of heat transfer were combined and suitable values substituted to yield:
\[
\Delta T = \frac{(5/9)(0.0498(28+0.3(T_{\text{air}}-T_{\text{water}}))-1.63\times10^{-9}((T_{\text{water}}+460)^4-T_{\text{sky}}^4)-(100(P_{w}-P_{dp}))))}{3}
\]

Where:
- \(T_{\text{air}}\) = daily average air temperature \([^\circ F]\)
- \(T_{\text{water}}\) = water temperature \([^\circ F]\)
- \(T_{\text{sky}}\) = sky temperature (calculated using \(T_{\text{air}}\) and dew point) \([^\circ R]\)
- \(P_w, P_{dp}\) = vapour pressure of water at water \(T\) and air dew point \([\text{in Hg}]\)

This equation was entered into a spreadsheet and used to estimate the temperature of the water in the tank in the early morning, based on the daily weather records for Elizabeth, NJ beginning with the measured temperature on January 3, 1995. The results are shown on Figure 11. The model does a good job of hindcasting the tank water temperature, within approximately ± 1°C. Although strictly accurate, the model would prove cumbersome to use in forecasting - dew points are not usually included in commonly-available long-range weather forecasts. As such, a simplified model was constructed that used an average daily net radiation (solar - re-radiated) and incorporated the evaporation/condensation heat transfer into the convective equation (i.e., evaporation/condensation are related directly to air and water temperatures in the simplified model, as opposed to the more correct vapour pressure difference in the rigorous model). The simple model is:

\[
\Delta T = \frac{(5/9)(0.0498(5+2(T_{\text{air}}-T_{\text{water}})))}{3}
\]

Surprisingly, this simple model, also shown on Figure 11, does an excellent job hindcasting the tank water temperature in January 1995 predicting temperatures within 0.5°C of Equation 3.

Figure 12 shows the daily change in heat content of the tank water predicted in January 1995 using the more rigorous model. During one period of significant warming the tank was gaining heat at up to 51,000,000 kJ/day, equivalent to a refrigeration capacity of 180 tons (using 11,400 kJ/hr = 1 ton).

Taking into account refrigeration efficiencies and available rental equipment capacities, a 525-ton portable chiller was installed to cool the tank water. This system consisted of a chiller unit (condenser, evaporator, compressor, and heat exchanger utilizing refrigerant R-22), an evaporative cooling tower to remove heat from the fresh water used to cool the condenser, and a 1250 kW diesel generator set. The portable chiller was set up beside the filter area at the north end of the tank, and plumbed into the filter discharge piping. Figure 13 shows the chiller equipment setup. Tank water was taken from the filter discharge at 7.6 m³/min (2000 gpm) directly through the chiller’s heat exchanger, cooled an average of 1.1 to 1.7°C (2 to 3°F) and returned to the piping that carried it to the south end, where it was reintroduced into the tank. The average residence time of water in the tank is 24 hours at a normal filtration system flow rate of 6.8 m³/min (1800 gpm). Figure 14 shows a plot of the measured tank water temperature (recorded first thing in the morning) during the period when the chiller was operating, compared to the recorded daily high and low air temperatures and the model’s prediction of what the tank water temperature would have been without the chiller. The chiller was started on January 10, 2002, and over the next few days cooled the water to -0.8°C (30.5°F). At this temperature the water passing through the chiller was being cooled sufficiently to begin forming ice crystals in the heat exchanger which were appearing on the surface of the tank. The ice
crystals were also reducing flow rates through the system and threatening to trip the automatic pressure drop shut off set point on the chiller control system. The temperature set points for the chiller were raised slightly to prevent ice crystal formation.

On a daily basis, the tank water temperature would increase by 0.25 to 0.5°C (0.5 to 1°F) due to the various heat inputs, with the greatest temperature increases noted on clear, warm, windy days. The tank temperature would decline overnight due to the effects of the chiller, re-radiation and cooler air temperatures. The chiller set points would be lowered during the day, to increase the amount of heat removed from the water passing through, then raised overnight, depending on the forecast overnight low, to prevent ice crystal formation. This worked well in maintaining the tank water in the desired range of -1 to -0.5°C (30 to 31°F) in the morning, preventing the tank from exceeding 0°C (32°F) by the end of the day. Ice slabs placed in the tank initially on January 14 were still intact on January 18. On the night of the 24th/25th of January the forecast low was 0.5°C (33°F), but the actual low was 7°C (45°F). The set points on the chiller had been raised in anticipation of the forecast low, so insufficient heat was removed from the tank overnight, and it started the morning of the 25th at a temperature of -0.3°C (31.5°F). By mid-afternoon the tank temperature had exceeded 0°C (32°F) and the ice slabs in the tank began to melt rapidly.

6 Test Ice Field Creation and Durability

When it was time to create, or replenish, an ice field for testing, the pallets were removed from the refrigerated storage containers with forklifts and carried to the side of the tank. The pallet was placed in front of a specially-built steel platform fitted on a second forklift, the plastic banding was cut off and the individual slabs were pushed on to the platform to lay side-by-side (Figure 15). The plastic divider sheets were recovered. The slabs were then chopped into the required sizes for the ice field (Figure 16). Generally, of the four slabs on the platform, one was chopped with a fire axe into four 0.6 m x 0.6 m (2'x2') pieces and one was smashed up with a pick axe into small chunks. The mix of chopped and smashed was varied from pallet to pallet in order to achieve the desired distribution of ice piece sizes.

Then, the platform was lifted up over the hand rail on the tank deck and tipped into a specially-designed steel chute that was positioned to slide the ice slabs and pieces over the deck and into the test area positioned alongside the tank wall (Figure 17). The ice was retained by 24"-oil containment boom positioned in the tank to form a 5 m x 76 m (16' x 250') rectangular test area along the west wall.

As each pallet was added to the ice field, the size and number of slabs and pieces was recorded. Occasionally, a full slab would fracture into two as it tipped over the edge of the platform or slid off the end of the chute. The first loading of sea ice into the Ohmsett tank took place on January 14, 2002. The required number of ice slabs was estimated at around 200 based on the area of the boomed test lane minus the area occupied by the skimmer, and the desired ice concentration. This was 4.9 m x 61 m x 0.9 (target ice concentration) / 1.2 m² (area of an individual slab averaging 39" x 48"). The thickness of the ice slabs grown at CRREL ranged from 21 to 28 cm (8.5 to 11 inches) with an average of 24 cm (9.5 inches). A total of 195 slabs of ice weighing an estimated 53 tonnes (58 tons) - based on an assumed ice density of 930 kg/m³ - were added to the tank over a time period of five hours and 43 minutes. Following an
initial learning curve to work out the loading procedure, ice was added at a rate of about 9 pallets (36 slabs) or 9.7 tonnes (10.7 tons) per hour. Due to favourable wind conditions, the ice naturally drifted away from the entry point building up from the far end of the test lane for the first four hours. At that point, the wind shifted and ice started to congregate around the entry point and the ice chute was shifted to the upwind end for the rest of the loading.

A small portion of the slabs broke in delivery or storage (5 out of 195) and a further proportion broke while sliding into the tank (15 out of 195). Table 1 summarizes the final composition of the ice sheet taking natural and induced breakage into account. The distribution of floe sizes closely matched the relative proportions recommended.

The ice sheet was observed the following morning (January 15) after a night of slight sub-freezing temperatures. A thin skim of new ice was visible in the openings between floes (likely associated with freezing of a thin layer of fresh surface water created by the melting ice). A layer of frazil ice could be seen floating on the water surface outside of the boomed test area (likely formed in the chiller, as discussed above). Floes were readily disturbed by lightly pushing with the pike pole. A series of photos were taken to document the composition of the entire 200 ft ice test sheet prior to any melting or disturbance (Figures 18 and 19).

Over the course of the day the water temperatures rose almost 0.5°C (1°F) in response to air temperatures in the high 40's and a clear, sunny sky sun. By early afternoon on Jan 15 (20 hours after adding the ice) most of the very smallest ice pieces had melted (representing an estimated 5-10% of the overall ice volume). Larger pieces (over 30 cm = 12" in size) showed minimal melting in terms of area and there was no measurable loss in thickness of the largest slabs.

By January 16, 48 hours after adding the ice, approximately 30-40% of the smallest ice was gone (amounting to about 6-8% of the total ice cover) and the remaining ice had reduced in thickness by an average of 5 to 8 cm (2 to 3 inches) to an average of 16 to 17 cm (6.5 to 7 inches). Much of this loss could have occurred late in the day on January 15, following the rise in tank temperature. Ice floe surface dimensions remained almost unchanged with the whole floes still measuring approximately 1.2 m x 1 m (48" x 39"). However, the floes were undercut by up to 2.5 cm (1 inch) all round with the bulk floe dimensions reduced to approximately 1.15 m x 0.95 m (46" x 37"). The floe sides tapered slightly from the waterline down. This represents a volumetric loss of 30% in the larger floes over 48 hours. Adding this value to the substantial reduction in the original brash ice the overall loss in ice volume at this stage (January 16) was estimated at 37%. In terms of area, the loss was less noticeable, estimated as approximately 10% of the larger floes (representing 93% of the ice) plus the melted brash ice proportion (8% of the total). This would indicate an overall loss in ice cover area in the order of 20%. Figure 20 shows a close-up of the ice on the morning of January 18, after 96 hours in the tank.

By midday on January 18, a further loss in ice concentration required the addition of 66 slabs (45% whole, 33% chopped and 12% smashed) to bring the overall ice concentration back to approximately 90% or 9/10. This would indicate a loss of ice area in the order of 30 to 35% over 96 hours with consistent daily air temperatures in the 40's and nighttime temperatures above freezing.

On the morning of January 22, 2002 a new half-sheet of ice was created at the
south end of the boomed area. This consisted of 20 pallets of ice with a distribution of 50% whole slabs; 28% quarter slabs; and, 22% small pieces. On January 23 and 24, a 100-ft long sheet of new ice was created at the south end of the boomed area using 33 pallets of ice. The distribution of ice sizes was 47% full slabs; 29% quarter slabs; and 24% small pieces.

On January 25 a further 5 pallets of predominantly small ice pieces was added to the field created January 23 and 24. The distribution (ignoring any melt loses in the intervening period) was then 42% full slabs; 26% quarter slabs; and, 32% small pieces. As noted above, the ablation rate of the ice increased considerably when the water temperature inadvertently crept above 0°C (32°F).

The durability of future ice sheets would be expected to improve as experience was gained in using the chiller system to maintain tank temperatures close to ~0.5 °C (31°F), to prevent melting. More representative winter temperatures would greatly extend the life of the test sheet. It is realistic to expect test ice sheets to last one week or longer with minimal replenishment under "normal" Ohmsett winter conditions.

7 Summary

Ohmsett, a 10-million litre, 35 ppt salt water test tank near Atlantic Highlands, NJ, is a location that does not favour the growth of ice in the winter. A detailed review of recent meteorological data from the area revealed that conditions that favour the growth of thin ice (ca. 1 cm) in winter at Ohmsett occur three years in five, or a probability of 0.6. The probability of thicker ice (ca. 25 cm) developing is 0.2 (one year in five). In order to conduct realistic testing in brash sea ice conditions at Ohmsett it was necessary to import the ice and cool the tank.

A review of the comparative characteristics of artificial sea ice (as grown in several test tanks around the world) and natural sea ice was undertaken to highlight their advantages and disadvantages for use at Ohmsett. Either was deemed acceptable for the planned program of skimmer testing. The principal characteristics of the test ice field for the planned program were:

- Ice field dimensions of 4.9 m x 76.2 m (16' x 250');
- Ice concentration of 9-tenths;
- Maximum piece size 1.2 m x 1.2 m x 20 cm (4' x 4' x 8''), based on the skimmer characteristics;
- Piece size distribution of 50% 1.2 m x 1.2 m; 30% 0.6 m x 0.6 m; 20% rubble < 10 cm (4''), based on an analysis of aerial photos of past spills in brash ice; and,
- Properties similar to level, first year sea ice grown naturally in near-shore waters.

There are two potential sources of sea ice in reasonable proximity to the Ohmsett test basin:

1. Ice grown in urea-doped water at the U.S. Army Corps of Engineers CRREL facility in Hanover NH; and,
2. Natural ice harvested near-shore along the New Brunswick or Nova Scotia coast in the Gulf of St. Lawrence, Canada (the preferred location would depend on logistics, ease of access, desired ice characteristics, local infrastructure etc.).

For a variety of reasons, primarily certainty of supply, the CRREL facility was
chosen to provide the ice. Approximately 164,000 kg (360,000 lbs.) of 20 to 25 cm (8" to 10") thick sea ice were grown at CRREL, cut into 1.2 m x 1.2 m slabs, placed on pallets, shipped to Ohmsett in refrigerated trucks and stored on-site in refrigerated containers.

In order for testing in brash ice conditions in Ohmsett to be feasible using either natural or artificially grown sea ice, the temperature of the tank water must be maintained below a maximum of 0°C (32°F) (above this temperature the ice will melt very rapidly) and above -1.7°C (29°F) (the freezing point of 35 ppt salt water). Ideally the water should be in the -1°C to -0.5°C (30 to 31°F) range.

A detailed heat transfer model for the Ohmsett tank was developed, using readily available local weather data, and calibrated using available tank water temperature data. The model was used to determine the required size of a chiller to cool the water to the target range during warm spells, and a heater to warm the water during cold snaps. Ultimately, a 525-ton portable water chiller was installed inline with the water filtration plant to control the tank water temperature within the desired range.

In preparation for testing, the pallets of ice were removed from the refrigerated storage containers, unpacked and cut into the appropriate sizes. The ice slabs were then loaded into the tank using a specially-constructed forklift attachment and a wheeled chute that moved along the deck of the tank. The pieces were contained in the desired test field dimensions by conventional oil containment booms. The test ice sheet survived for 4 days without significant area or volume losses during a winter with close to record high air temperatures. With the experience gained from this project, and more normal “winter” temperatures at Ohmsett, it should be possible to maintain a representative brash ice field in the tank for a week, or more.

8 Acknowledgements
This study was funded by the U.S. Minerals Management Service. The authors would like to acknowledge the invaluable assistance of the staff of MAR, Inc. who operate Ohmsett under contract to MMS, and the staff of CRREL who grew, cut, packaged and shipped the ice.

9 References


 Canadian Hydrographic Service, *Sailing Directions: Gulf and River St. Lawrence - 6th Ed*, Fisheries and Oceans Canada, Ottawa, 1992


Figure 1  30-year Median Ice Concentrations for January 1

Figure 2  30-year Median Ice Concentrations for January 8
Figure 3  30-year Median Ice Concentrations for January 15
Figure 4  Measured Sea Ice and Snow Thickness at Caraquet, NB
Figure 5   Measured Sea Ice and Snow Thickness at Summerside, PEI
Figure 6  Harvesting Ice at CRREL

Figure 7  Stacking Ice Slabs on Pallet
Figure 8  Unloading Ice from Refrigerated Trailers at Ohmsett

Figure 9  Pallets in Refrigerated Storage Container
Model of Heat Transfer to/from Ohmsett Tank Water

![Diagram of heat transfer models](image)

Vol = 2.6 x 10^6 gallons seawater; Mass = 22.14 x 10^6 pounds

Figure 10 Modes of Heat Transfer Considered for Ohmsett Model

Heat Transfer Models of Water T at Ohmsett

![Graph of heat transfer models](image)

Figure 11 Comparison of Measured and Hindcast Tank Water Temperatures
Figure 12  Predicted Daily Heat Loss/Gain from Tank in January 1995

Figure 13  Portable 525-ton Water Chiller Unit
Effect of Chiller on Tank Water Temperature

- - - - Recorded Daily High
- - - - Recorded Daily Low
△△△ Measured in a.m.
- - - - Predicted Tank Water - No Chill

Ice crystals on tank
Chiller on
Ice melt - T>32°

Figure 14  Tank Water Temperatures in January, 2002
Figure 15  Putting Ice Slabs on Lifting Platform

Figure 16  Ice Slabs being Chopped into Pieces
Figure 17  Ice being Added to Tank

Figure 18  View of Test Lane after Completion of First Ice Loading
Figure 19  Close-up of Ice in Test Lane the Morning After Loading

Figure 20  Ice Conditions in the Test Area on the Morning of January 18
<table>
<thead>
<tr>
<th></th>
<th>Whole Slabs (39” x 48”)</th>
<th>Smaller Pieces (typ 24” x 24”)</th>
<th>Brash (typ less than 4”)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target Proportions</td>
<td>55%</td>
<td>27%</td>
<td>18%</td>
</tr>
<tr>
<td>Achieved Proportions</td>
<td>52%</td>
<td>29%</td>
<td>19%</td>
</tr>
</tbody>
</table>